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Managing climate risks on the ranch with limited drought information

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ABSTRACT

Ranching involves complex decision-making and risk management in the face of uncertainty about climate conditions. The profitability and sustainability of ranching depend heavily on sufficient and timely rainfall for rangeland forage production. As a result, ranchers may either adopt conservative long-term stocking strategies as a hedge against drought or practice a more dynamic approach in which they vary stocking rates and supplemental feed in response to drought. Yet, some strategies require more information about climate risks than is often available to ranchers. We review the literature to draw out the drought management options as well as the tools and products for drought monitoring and early warning that are available to ranchers. We find that a large gap remains between the information needs of ranchers seeking to adapt dynamically to drought and the information that is available. Moreover, even when actionable information is available, it is unclear whether ranchers are optimally incorporating that information into their risk management decisions. Further research is needed to understand how to package existing information into risk management decision tools in a way that addresses cognitive and operational barriers to support timely decisions that will reduce the impact of drought on profits and the long-term sustainability of rangelands. Due to the multi-faceted nature of climate risk management in ranching, further study of ranching behavior and decisions has the potential to bring new insights into climate risk management and decision and risk theory far beyond the field of ranching and agriculture.

1. Introduction

Livestock ranching on semi-arid rangelands involves some of the most complex decision-making of any natural resource production and land use system. Ranchers continuously adjust to weather, climate, and range conditions that affect livestock production. They must also respond to weather-sensitive swings in feed prices and cattle markets. Studies of ranchers' drought management strategies can offer lessons for complex decision-making in a variety of weather- and climate-sensitive sectors. Insights gleaned in this setting have the potential to improve our understanding of universal problems in decision-making under uncertainty.

Pastoralism has long been studied as a dynamic socio-ecological system (Galaty and Johnson, 1990), and as an exemplar of human adaptation to environmental variability. In their review of global pastoralism studies, Reid et al. (2014) identified a set of key insights into how pastoralists use movement, collaboration, market hedging, and other adaptive mechanisms to thrive despite the considerable natural variability typical in semi-arid rangelands, where "vegetation and water resources are usually ephemeral in time

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and patchy in space" (p. 219). They noted that flexibility and adaptability, hallmarks of range livestock production, are necessitated by the uncertainty inherent in rangelands, which exhibit nonlinear dynamics, difficult-to-identify tipping points, and responses to different grazing pressures. For example, climate variation can either amplify or attenuate the effect of grazing pressure in determining rangeland ecosystem behavior (Briske et al., 2005; Ellis and Swift, 1988; Wehrden et al., 2012). Livestock production in the western U.S., regionally referred to as ranching, is a form of pastoralism that has evolved into an adaptable natural resource production system exhibiting complex interactions among weather and climate, range condition, cattle and land management, markets, socioeconomics, and policy. Utilizing 55% of land in the United States and producing $64 billion of cattle in 2016, cattle ranching is an important industry that warrants more attention in climate risk management (USDA Economic Research Service, 2017; USDA, 2016). In this paper, we focus our discussion largely on cow-calf production in the Rocky Mountain and Plains regions in the United States.

While ranching depends on many aspects of the climate, drought is the key natural hazard in western U.S. range livestock production. Drought reduces the forage supply on which cattle weight gain and revenues depend. In the case of the 2012–2013 North American drought, 59% of rangeland and pastures were classified as "poor" or "very poor" conditions for more than a month, indicating that forage supplies were far below normal (Rippey, 2012).

A drought-induced drop in forage supply can have macro impacts on cattle markets leading to a series of revenue losses and cost increases for cattle producers. If widespread drought causes many producers to cull their herds simultaneously, then the flood of supply to cattle markets can cause prices for cattle to drop significantly (Scasta et al., 2016). In the 2010–2013 drought, Texas alone suffered a record $3.23 billion dollars in livestock losses, with some states losing up to 23 percent of their pre-drought cattle inventory (Guerrero, 2012; Rippey, 2012).

Drought may also raise the cost of adaptation measures, through increased demand for rental pasture and supplemental feed. These price increases put a further financial strain on producers that need to undertake drought adaptation to hold on to their herds through periods of low forage growth. When the cost of feed and rental pasture is too great, ranchers may sell cattle they cannot afford to feed resulting in widespread herd reductions and a cattle market in oversupply, which leads to reduced cattle prices received by producers.

Selling early to avoid this crunch comes at a cost: ranchers secure a better price per pound, but sell lighter cattle than if they kept them on the range or supplemental feed and sold them later in the season. Once prices drop, producers have an incentive to try to hold on to their herd to wait out the drought and the depressed market, but this incurs other costs. They either pay for costly adaptation methods such as buying hay and renting pasture or leave their herds on a drought-compromised range, which reduces livestock performance. If cattle are left to graze beyond what is optimal for the rangeland ecohydrology and plant recovery, then the damages may affect long-term forage potential and future profitability as well as create negative impacts on ecological resources on the rangelands and in nearby riparian zones. These decisions and their outcomes are part of a complex, sequential chain of climate risk challenges on the ranch.

This review examines the literature relevant to the choices that ranchers make in the face of drought; the goal is to extract findings that situate the range livestock system in the context of climate risk management (Travis and Bates, 2014). Rangeland livestock producers have developed a complex suite of strategies and tactics that can inform other aspects of climate risk–such as the expected utility of sequential decisions under uncertainty, value of additional information such as drought monitoring and forecasting, and risk aversion and risk transference tools like insurance. We look first to the relationship between climate and cattle production starting with forage growth and ending at cattle sales. We then examine the drought response on the ranch: what options are available to adapt to climate variability and how can the tools and theory of decision and risk analysis help ranchers make better choices. Finally, we assess a critical piece that could be a significant barrier to optimal drought adaptation: the availability of information about drought monitoring and prediction and how climate change might affect drought frequencies, the usefulness of drought information, and the ranchers' drought responses. How ranchers handle drought risks even while facing a dearth of climate information lends insight into broader questions of climate risk management. It is important to understand both what is needed to help bring about more optimal climate adaptation, but it is also crucial to know how to adapt when good information is simply not available.

2. The drought-ranching connection: from the atmosphere to the sale barn

This section is organized by the links and sequential decisions in the range livestock production system, starting with drought and working through ranch operating decisions to final marketing. Our archetype ranch is a cow-calf enterprise, common in the American West, that maintains a "mother herd" and raises calves, born in the spring each year to be sold at auction typically in the fall (Tess and Kolstad, 2000). Variations on this system exist across the West, with some ranch enterprises keeping calves into a second year, grazing year-round in the desert ranges, taking on cattle from other operations, and other strategies typically aimed at further managing range and market variability (Wilmer et al., 2017). Some ranches include irrigated hay production to supplement range forage, and this is used especially to feed the mother herd through winter; but even on these ranches, rangeland provides the main source of forage.

Precipitation, forage growth, calving rate, weight gain, and sale price are critical variables in the range livestock production cycle and are among the variables commonly found in ranch simulation models and management tools. In addition to a linear flow from one factor to the next (Fig. 1), many of these variables interact with other factors on a complex scale. For example, as discussed above, market prices are affected by large-scale climate conditions through the climate-driven behavior of producers. The foundation and starting point is the interaction of climate and range: in the semi-arid rangelands of interest here, more precipitation typically yields more forage, which generally translates into greater cattle weight gain (or less supplemental feed to achieve a target weight).

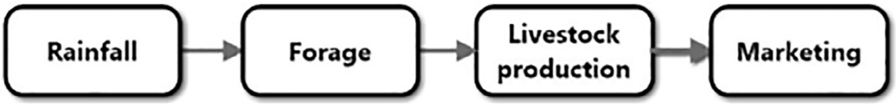

Fig. 1. A simple schematic of the linear flow from rainfall to cattle sales.

2.1. From rainfall to forage

The critical first link in climate and ranching is between precipitation and forage production (Murphy, 1970; Cable, 1975; Duncan and Woodmansee, 1975; Lauenroth and Sala, 1992). This relationship can be evaluated with two temporal scopes: short-term swings in forage production due to seasonal and intra-seasonal variation, especially drought, and long-term range production that sets the land's carrying capacity or sustainable stocking rate.

2.1.1. Short-term rainfall: inter-annual and intra-annual variation

An abundance of literature documents a positive correlation between precipitation and forage growth in semi-arid climates like the American West (Yang et al., 2008; Cable, 1975; Houerou and Hoste, 1977). The relatively straightforward relationship between average monthly precipitation and forage growth potential in the western U.S. was used by the Agricultural Research Service to create the "Drought Calculator"– spreadsheet decision tool to help ranchers and range managers predict forage reductions due to drought, based on observed monthly precipitation (Dunn et al., 2013). In calibrating the drought calculator with site data on precipitation and forage, Dunn and colleagues account for 83% of the variation in forage growth with monthly precipitation alone. After reviewing a number of studies, Holechek finds that forage production can fluctuate 30% between good and bad rainfall years (Holechek, 1988).

Similar work supports this pattern of more precipitation leading to more forage, though the optimal temporal pattern of precipitation varies for different regions. For example, in North Dakota, June is the critical month for precipitation that yields forage growth (Dunn et al., 2013). Rainfall earlier in the growing season is important farther south: Smith (2007) and Dunn et al. (2013) find that for most of Wyoming middle-elevation ranges, April precipitation is key to establishing forage. The southern Great Plains and southwestern deserts support light year-round grazing depending on summer and winter precipitation (Thomas et al., 2015).

These intra-seasonal weights on forage production define key decision points. For example, for middle-elevation ranges in Wyoming, if there is a precipitation deficit by the end of April, then it is unlikely that precipitation in later months will be able to fill the gap. This means that with an early deficit, drought management strategies should be decided upon by the end of April (Smith, 2007). While the temporal effect of precipitation on forage varies across rangeland geographies, critical periods in the Great Plains and the Rocky Mountains, the region of interest for this review, tend to be spring and fall (both Dunn et al. (2013) and McCuistion et al. (2014) used climate data only for the spring and fall seasons). Winter and spring precipitation sets the basis for the initial spring growth, commonly known as the "green-up" of western ranges. Summer precipitation, which typically exhibits high variance in these regions, can add forage up to a point at which grasses mature and the correlation falls off. Fall precipitation affects cool season growth as well as winter forage conditions.

It is not only the quantity of forage that matters for cattle growth but also the nutritive quality. Forage nutritive quality is affected by, but not as tightly correlated with, rainfall. McCuistion et al. (2014) tested the relationships among precipitation, season, temperature and forage nutritive quality, indicated by the amount of acid detergent and crude protein in the forage, two variables important to overall livestock health. Crude protein is the primary nutrient that livestock derive from forage, while acid detergent fiber (ADF) is the indigestible part of the forage that decreases the overall nutritive value. They found that for a ranch in South Texas, monthly precipitation in the fall explained 62% of the variation in crude protein and 57% of the variation in acid detergent fiber (McCuistion et al., 2014). With temperature and monthly precipitation included, the regression model accounted for substantial additional variation in acid detergent fiber (73%), but not crude protein (63%). However, the study did not include interaction effects between temperature and precipitation. The importance of precipitation and temperature points towards a clear role for climate risk, particularly since both precipitation and temperature patterns change over time.

How a particular range will respond to precipitation deficits depends on ecosystem type (Moran et al., 2015) found that mesic grasslands, characterized by wetter soils more common in the Great Plains, are more resilient to drought in terms of productivity than are the xeric, desert grasslands of the Southwest. This study also finds that mesic grasslands are heavily influenced by both the current and previous year's precipitation and are more resistant to compositional species change than the desert grasslands. The plains grasslands are described as unique in that they evolved under grazing pressure which has resulted in greater resistance to production loss and compositional change, and greater regenerative capability. Under persistent drought, desert grasslands are more susceptible to vegetation die-off and invasive species leading to a higher likelihood of transition to alternative states, like a woodier shrubland.

The Moran et al. study corroborates others that predict significant region-dependent changes in the productivity and composition of American grasslands as a response to drought and that resilience to forage loss is generally proportional to mean annual rainfall (Huxman et al., 2004; Knapp et al., 2015). This varying sensitivity to drought means that ranchers not only need good drought information, but also accurate, specific information about the ecological composition and likely responses of their rangeland.

Range simulation models dive deeper into the relationship between climate factors and forage by exploring ecological interactions of soil and plant life, and could provide such information. These models are built to explore the interplay between rangeland grazing and ecological responses, but they are not generally meant to inform ranching decisions and can be difficult to access and interpret.

Table 1
Major range simulation models.

Model	Description
Century	The Century 5.0 Model is designed to simulate various nutrient cycles in four different plant-soil environments: grassland, forest, agricultural crop, and savannah systems. The Century model is primarily used for timescales of centuries to millennia but has recently added a daily time-step version, called DayCent5. DayCent5 includes trace gas and soil temperature sub-models (Ojima, 2006).
Phygrow	The Phytomass Growth Model primarily models forage consumption, above ground shrub/herb growth, and hydrologic processes. It also determines how animal populations, weather, and varying landscapes affect forage production. Phygrow is unique in that it presents near instantaneous assessment for present and future forage conditions (B.R. & . E. Center, 2017).
APEX	Agricultural Policy/Environmental eXtender Model (part of the Environmental Policy Integrated Climate (EPIC)) is a watershed simulation model. APEX's purpose is to evaluate different land management strategies while considering variables such as (but not limited to) soil quality, sustainability, economics, and plant competition (Wang et al., 2012).

We do not review them in detail here, but several links in such models emulate the chain of effects and decisions we do address; a range process model may be a logical module of more complex range/ranch decision models and may in future provide more actionable information. Table 1 provides brief summaries of the major rangeland models.

2.1.2. Long-term rainfall: climate and range carrying capacity

Climate interacts with edaphic factors like soil and plant community to determine the long-term productivity of rangelands (Holechek et al., 2010). Determining sustainable stocking rates was one of the first significant challenges of range science as it emerged in the middle of the 20th century (Harlan, 1958; Reppert, 1960; Bement, 1969; Fleischner, 1994; Thomas et al., 2015). Target stocking rates were needed to specify the utilization levels of federal rangelands for grazing permits and soon became a measure of productivity on private lands too.

A stocking rate is simply the number of animals on a unit of land per unit of time (Redfearn and Bidwell, 2000). Most commonly, this is expressed as Animal Unit Months or Animal Unit Years. An animal unit is an index with a 1,000 lb lactating cow and her calf equal to 1 Animal Unit (AU). A 1200 lb cow with a calf is equal to 1.2 AU, and an 800 lb cow with a calf is equal to 0.8 AU. Weaned calves have a slightly different scale on the index with a 600 lb calf, such as a yearling, equal to 0.7 AU. AUMs are commonly used to account for the fact that due to different lengths of growing seasons, not all pastures are grazed all year round.

Choosing a stocking rate is the most important decision a rancher makes because it has a significant impact on his profitability and long-term sustainability (Holechek, 1988; Redfearn and Bidwell, 2000). Following Holechek and coauthors (Holechek et al., 1999), we define the intensity of stocking in terms of the percent edible forage utilized by the herd where light grazing is, on average, 32% forage utilization, moderate grazing is 43%, and heavy grazing is 57%. The conventional wisdom of "take half, leave half" of the forage is moderate and recommended, but this advice may only apply to ranges on humid or annual grasslands (Holechek, 1988). A sustainable utilization rate on a humid grassland would lead to range degradation on a more sensitive range (Thomas et al., 2015). The level of utilization that is considered moderate varies from 25 to 35% for desert shrubland to 50–60% for Southern pine forest or Eastern deciduous forest (Holechek, 1988). Conservative stocking is the light-to-moderate use of about 35% (Holechek et al., 1999). Thomas et al. (2015) suggest even lighter stocking rates for desert ranges, which provide a buffer for drought and still return positive financial outcomes. Recommended stocking and utilization rates for drought conditions are much less well established than those for periods of normal rainfall. Hart and Carpenter (2005) estimate that across the Great Plains and Mountain West that the carrying capacity of the range during drought may be 50–70% of that in a typical year.

Two main stocking strategies are recommended in the ranching literature: conservative or light stocking that provides a standing buffer for drought periods and moderate-to-heavy stocking with timely destocking during drought years. Conservative stocking rates leave forage on the ground (and profits on the table) during normal rainfall years. But, when a drought hits, the conservative stocking rate sustains the herd, profits, and rangeland where a heavier stocking rate would lead to losses on all three fronts. Conservative stocking is a low-risk strategy that pays off during droughts and drought can be a rancher's biggest source of risk. Studies comparing conservative to a moderate stocking rate yield different results in different rangelands. In drier rangelands, ranchers lose out on 10–25% of revenues during normal rainfall years if they stock conservatively but enjoy 30–60% higher returns during severe drought (Holechek et al., 1999). Thomas et al. (2015) find that light stocking is the most profitable long-term strategy on desert ranges. Essentially, conservative stocking is a low-risk, low-return strategy that requires little in terms of dynamic drought forecasts or active drought management.

Flexible stocking may have the potential to increase the profitability of ranching without damaging long-term rangeland sustainability in some range and climate settings (Díaz-Solís et al., 2009), but it requires climate information that is not available or not reliable. A study that used a dynamic optimization model to compare conservative stocking to flexible stocking found that flexible stocking with cow-calf and yearling enterprises, under perfect climate information, could double net returns compared to conservative stocking with cow-calf and yearling enterprises (Torell et al., 2010). In the same work, Torell and coauthors found that as forage production variability increased, so too did the value of flexible stocking. In a survey of Wyoming ranchers, Kachergis et al. (2014) find that, in response to drought, 24% of those surveyed sell retained yearlings and 80% reduce herd size. They also find that keeping yearlings for added flexibility was associated with lower reported drought impacts.

2.2. From forage to cattle production

Cattle production is determined by weaning percentage and calf weight gain. Weaning percentage is the proportion of cows in the herd that gives birth and successfully weans a calf. Calf weight gain is the total weight put on by a calf over a period of time and weaning weight is the calf's weight at weaning. Baseline cattle characteristics, such as calving weights and body condition, are set by the genetic selections made by ranchers over time, and some recent literature suggests more effort to fit animal genetic parameters to the climate and range (Scasta et al., 2015). In western cow-calf operations, calves generally weigh 60–80 lb when they are born and 500–650 lb by the time they are weaned from the mother cows.

Both weaning percentage and weight gain are highly dependent on forage – and thus, rainfall. Weaning percentage is a critical factor in the profitability of cow-calf operations and is strongly related to the forage and supplemental feed made available to cows. The birthrate is strongly influenced by body condition. Body Condition Scoring (BCS) is a numeric system from 1 to 9 that estimates the body energy reserve of the cow. A score of 1 indicates an emaciated cow, and a score of 9 indicates an obese cow (National Academies of Sciences Engineering and Medicine, 2016). Research points to a strong correlation between BCS and reproductive performance; cows with a BCS of 5 or greater had a pregnancy rate of 85% or higher, while cows with a BCS of less than or equal to 4 had a pregnancy rate of 60% or lower, all else being equal (Eversole et al., 2009; Rae et al., 1993). BCS, in turn, is determined in large part by forage quality and quantity. Without adequate forage, cows will become thin, leading to a low BCS score (Eversole et al., 2009).

Available forage is the key factor for cattle weight gain. Numerous studies, algorithms and extension literature address this critical link. Harlan (1958) developed the first set of general curves for weight gain on different ranges at different grazing intensities. Because forage production is mostly controlled by precipitation in the western ranges, some of the literature skips forage itself and simply correlates rainfall with weaning weight. Many models use precipitation as part of their prediction of weaning weight, but do not directly use it as the sole predicting variable (Gillard and Monypenny, 1990; Vantassell et al., 1987). In the cow-calf production system that is the focus of this study, research has found a positive correlation between precipitation and weaning weight (Scasta et al., 2015; Vantassell et al., 1987). Scasta et al. (2015) find that for each inch reduction of rainfall, weaning weight decreases by 7–14 lb (Scasta et al., 2015). Vantassell et al. (1987) examine calf weight gain and find that a calf's rate of growth increases as precipitation increases with an asymptotic limit. Moreover, Grings et al. assert that reduced precipitation also reduces forage nutritional value and can further affect calf weight gain (2005).

2.3. From production to sales

With perfect credit and risk-pooling markets, ranchers seek to maximize their profits. The picture becomes more complicated if those assumptions about perfect markets are relaxed. Namely, risk aversion begins to play a significant role in decisions when exposed to uninsured risks inherent in ranching (Karlan et al., 2014). The simplified approach to understanding ranching decisions is that ranchers try to maximize revenues while minimizing the costs of production. Revenues depend on the number of cattle they sell, the quality and weight of those cattle, and the market price.

Cattle prices have ranged around $100–$230 per hundredweight in recent years (Fig. 2a). Prices vary seasonally; cow-calf operations tend to market cattle in late fall of every year (e.g., Oct-Nov) to avoid the costs of over-wintering calves produced that spring. Because of the popularity of this production strategy, cattle supply tends to be high in the fall and, as a result, prices decrease (Brooks, 2015). Different weight classes experience different price patterns (Fig. 2b), but most show the fall slump. Ranchers with ample over-winter forage can employ alternative strategies that avoid or leverage the fall price slump. Ranchers can avoid low fall prices by holding and feeding calves over-winter to become "yearlings" that can be sold anytime in their second year (Hart and Carpenter, 1999; Torell et al., 2010; Derner and Augustine, 2016). Others buy "stockers," typically another rancher's calves or yearlings that can gain weight on the ranch given sufficient forage (Hart and Carpenter, 1999; Torell et al., 2010; Derner and Augustine, 2016). This strategy is profitable if the marginal cost of adding weight to the stockers is less than the additional revenue they will bring in when sold. If ranchers have excess forage available or if hay prices are low, then the low marginal costs may add to the profitability of this strategy by allowing them to take advantage of price arbitrage across seasons. Having yearlings in the herd can also add valuable flexibility in forage demand since they are already weaned and can be sold at any time. This strategy is seen as an adaptation to variable forage production; the drought adjustment literature recommends some inventory of cattle that can be sold at early signs of drought (Derner and Augustine, 2016).

The cattle cycle is, historically, a varying period of roughly ten years in which the national herd size rises and falls due to inherent features of cattle production life-cycles, climate trends, and broader market fluctuations. Shocks to the production system, such as drought, disease, or swings of supply and demand in the market, may force a rancher to destock. Following the shock, with a recovery of price and rangeland forage levels as an example, there is a multi-year lag between the restocking of a herd with new heifers and the ability to sell their offspring at profitable prices (Norton, 2005; Crespi et al., 2010). Producers will try to take this pattern into account as they decide when to restock and when to sell and this adds another contributing factor to the cycle (Hamilton and Kastens, 2000). The interaction of these factors typically drives the national inventory to grow for 6 or 7 years and shrink for the several years following, with an intermediate recovery phase that lasts another year or two (Norton, 2005).

Drought is known to cause ranchers to cull their herds (to match reduced land carrying capacity as described earlier), and widespread drought increases the supply of cattle to the market, which depresses prices and exacerbates the cattle cycle. The 2012–2013 drought that affected much of the American Southwest was the most severe drought in the Southern Plains since the 1930s (Hoerling et al., 2012), and it caused a significant drop in the national cattle inventory (Kachergis et al., 2014). Rebuilding

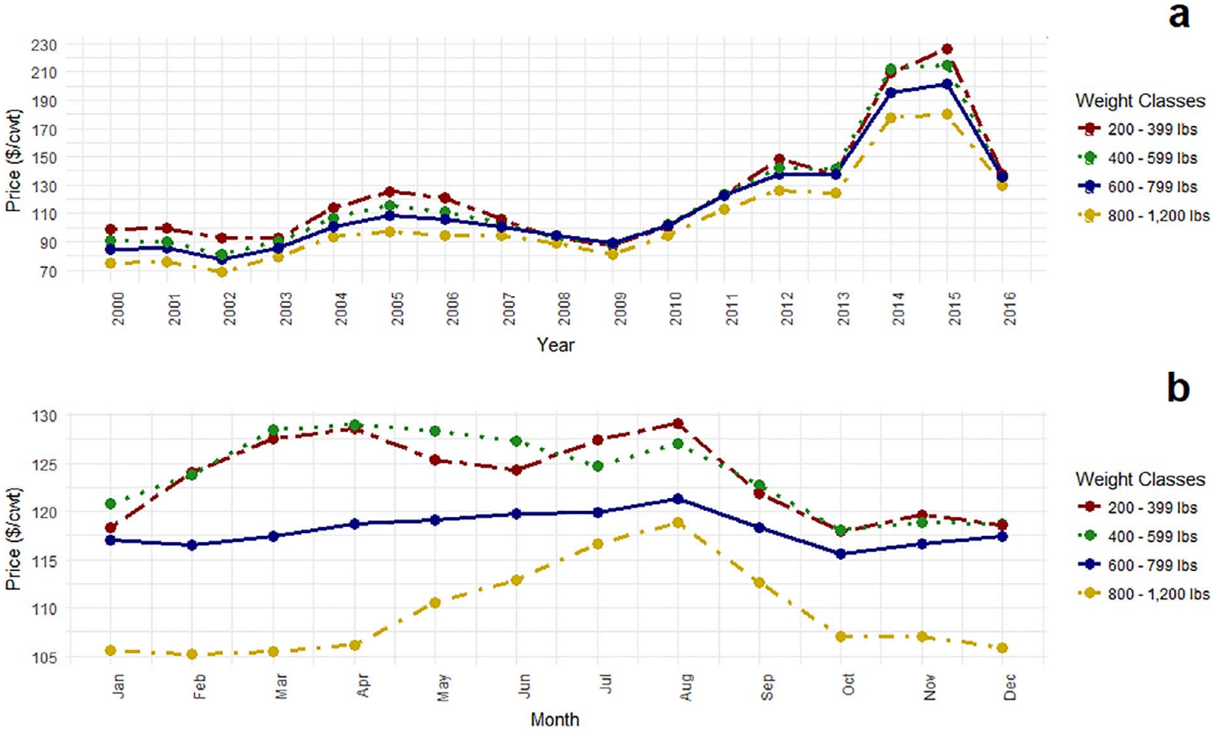

Fig. 2. a: Average yearly sale price as dollars per hundred-weight for four weight ranges at U.S. cattle auctions from 2000 to 2016. b: Average monthly sale price as dollars per hundred-weight for four weight ranges at U.S. cattle auctions from 2000 to 2016 (USDA-RMA, 2016).

herds takes time and may be delayed by continued drought or expectations about continuing drought. In this situation, ranchers without cost-effective drought alternatives are forced to sell into a depressed market. Those who can arrange for alternative feed or grazing, and thus hold on to the herd, may try to wait for prices to rebound. In fact, prices tend to rise above average levels after a drought when supply is low due to reduced regional and national inventories and higher demand as ranchers buy animals to rebuild their herds (Bastian et al., 2006).

3. Drought response on the ranch

Ranchers practice strategic climate risk management by choosing among a well-known set of drought responses (Coppock, 2011; Scasta et al., 2016; Kachergis et al., 2014). While the roster of options is well-developed, the decision process in the face of uncertainty is complex and less well studied. As Ritten et al. noted, ranch decisions are "complicated by variable range forage production caused largely by stochastic precipitation, and such decisions must often be made before growing season precipitation is realized" (Ritten et al., 2010b). Long- and short-term herd management decisions must be calibrated to changing expectations of long- and short-term forage, weighing likely outcomes both in terms of economic returns and range ecosystem conditions (Derner and Augustine, 2016). The climate risk management challenge in semi-arid grazing systems is to integrate decision analysis and drought information to reduce risks and improve productivity.

In terms of decision theory, producers operate in two major realms: expected utility under uncertainty and strategic or game behavior whereby they try to anticipate the behavior of other producers (whose choices affect cattle and feed prices) and the government (which can offer supports like subsidized feed or other drought emergency programs). Producers navigate this complexity with a mixture of tradition, intuition, analysis, and external advice, mediated by their risk perception and risk aversion.

The daunting drought decision challenge was evident during the 2011–2012 drought that caused the largest sell-off of the nation's cattle herd in recent history:

> A [Kansas rancher] sold 20 pairs of cows and calves a few weeks after drought had sucked his pastures dry and no rain was in the forecast. He sold 20 more pairs Friday. [The rancher] spent years meticulously breeding his cows to improve the genetics each generation, but with Kansas in one of the worst droughts in decades, he's struggling to find enough grazing to feed 300 cows, plus their calves. He hopes to get by with selling only a quarter of his herd, but there are no guarantees with the drought expected to linger through October (Hegeman, 2012).

The news article further reported on the widespread sell-off which brought the national inventory to a 40-year low and depressed cattle prices. It also described the fraught cycle in which ranchers cull herds en masse to save their pastures, selling into flooded markets at low prices, and later are forced to buy replacement animals at higher prices. One strategy would be to buck this trend, which is illustrated in another quote: “If you can figure out a way to hang on to them at a reasonable cost until the drought is over, it typically pays you pretty well” (Hegeman, 2012). Holding on means finding alternative feed or pasturage. But the urge to hold on even as drought worsens is often cited as a cause of long-term rangeland degradation (Knutson and Haigh, 2013; National Drought Mitigation Center, 2013). Much of the drought advice provided to ranchers warns against that strategy and, instead, encourages flexible and dynamic adaptation including reductions in herd size to meet changing range conditions (Derner and Augustine, 2016).

Each drought adaptation choice has cost and revenue implications for the ranch enterprise, as well as potentially lasting effects on range ecosystems. Extra feed purchased in anticipation of drought-induced shortages later in the growing season may prove to have been an unnecessary expense that diminishes profitability. Waiting to see if the drought continues before taking action may mean coming up short on forage, buying hay at drought-inflated prices, selling cattle earlier at lighter weights than planned, or stressing the range by grazing at a greater intensity than its drought-reduced productivity supports. The latter effect cascades into future seasons as range recovery is slowed and under-fed cows produce fewer calves. Ritten et al. (2011) argue that if a range is degraded during the drought, then it takes substantial time to recover once the drought is over and it becomes susceptible to invasive species that may reduce forage production. In the worst case, ranchers may find themselves degrading range productivity, buying expensive feed, renting pasture at inflated prices and, finally, selling into a market flooded by other producers who are also culling their herds (Hegeman, 2012). They then pay a premium to rebuild herds in the drought’s aftermath (Gee, 2015; Doye et al., 2013). With that intense cascade of impacts, it is hardly surprising that in 2015, with the industry in recovery from the 2012–2013 drought, the Wall Street Journal could still find aversion to climate risks, quoting a rancher who was waiting to expand his herd back to its pre-drought levels: “I’m not willing to spend $2,000 or $2,500 for a bred heifer and not know if I can make a profit next year… I’m not sure the drought is over” (Gee, 2015). It is no wonder that one set of guides to ranch-drought management is sprinkled with suggestions for maintaining mental and physical health and family well-being through such stressful periods (Knutson and Haigh, 2013; National Drought Mitigation Center, 2013).

Such loss scenarios only play out if, indeed, drought continues. With uncertainty about even near-term future conditions – Will the drought continue? Will it worsen? – it is only in hindsight, with the knowledge that the drought did, indeed, continue and worsen, that early adaptive decisions seem justified. Extension advice to act early in drought goes against informal decision processes in which the rancher discounts the potential for future loss and focuses on the costs of early adaptation. Indeed, in the absence of skillful forecasts of drought conditions over future months and seasons (Hoerling et al., 2012; Crimmins and McClaran, 2015) the producer who chooses no action in the early stages of drought may well be wise, especially since most dry spells do not become extreme droughts. Yet there is a tendency for droughts in some parts of West to persist for multiple years (Ault et al., 2014), leaving every rancher to ponder the unknowable: whether a drought year is the first of several or a singular event. Even if early action is optimal, ranchers may delay due to loss aversion, ambiguity aversion, or simply a rational hesitation to make irreversible decisions under uncertainty (Ellsberg, 1961; Kahneman and Tversky, 1979; Hogarth and Kunreuther, 1989; Dixit and Pindyck, 1994; Moschini and Hennessy, 2001).

This risky decision making invokes a ranching strategy observed by range economists for decades: conservative long-term stocking rates that provide a buffer to drought impacts but fail to capture higher productivity when conditions are good (see, for example, Smith and Foran (1992, 2010)). This strategy is observed in other resource systems in which productivity varies and is difficult to predict and monitor, like fisheries (Coulthard, 2009) and dryland cropping (Farahani et al., 1998). Ranchers, however, can adjust many aspects of their herd and land use on short notice and at several points in the annual cycle; the challenge during drought years is to break tradition and make those hard choices, suggesting that there is potential for more adaptive drought risk management in the industry (Derner and Augustine, 2016).

3.1. A role for decision tools

In many ways, the field and tools of decision analysis (Howard and Abbas, 2016) emerged to remedy the inefficient and negative outcomes of intuitive decision-making under uncertainty that show up in many resource management systems and is inherent to climate risk management (Travis and Bates, 2014). A main climate risk management challenge in western ranching is to make the trade-off between early adaptive decisions and future outcomes more explicit in ranch management and decision support tools. Clear and accurate drought monitoring and forecast information are needed to inform drought adaptation decisions.

As with agricultural economics research more widely, concepts of risk management and decision analysis entered the range economics literature in the 1960 and 1970s (Rogers and Peacock, 1968; Whitson, 1975), and led to efforts to prescribe optimal decisions in ranch operations (e.g., Rodriguez and Taylor, 1988). Over the past three decades, a body of detailed analyses of ranch decision-making has accumulated (Carande et al., 1995; Ritten et al., 2010a; Ritten et al., 2010b). The literature reflects a long-standing operational question about adapting ranching to weather and climate variability: whether in general it is better to face weather and forage variability with a static, conservative long-term stocking rate or to vary herd size and grazing patterns dynamically to adapt to changing climate and range conditions (see, for example, Smith and Foran, 1992; Torell et al., 2010). Recent analyses have pointed toward the value of dynamic decisions that are responsive to changing conditions, especially during droughts (Derner and Augustine, 2016). Ranchers who wish to follow advice of some range researchers and adopt more dynamic responses to drought (Ritten et al., 2011; Schmidt, 2007; Beutler, 2006), thus placing more emphasis on rapid response and informed decision-making along with nimble financial management (Hoag, 2009; National Drought Mitigation Center, 2013), will require better drought information. Ranchers have long used spreadsheets to manage their enterprises, and extension services and consultants provide spreadsheets to help in many decisions, from herd management to financial choices[1]. A large gray literature, chiefly extension bulletins and newsletters, addresses specific issues important to drought response, such as whether to hold or sell calves in a drought (Gill and Pinchak, 1999; Hart and Carpenter, 1999); the role of flexible herd management by adding "stockers" or holding on to calves into a second year (Smith and Waggoner, 2005); whether or not to purchase insurance (Sedman and Hewlett, 2014); and the financial and tax implications of different drought responses (Tronstad and Feuz, 2002; Schroeder and Ehmke, 2008; Ritten et al., 2010b). Some of these tools inculcate principles of decision analysis, such as trade-off and sensitivity analysis, but most do not make probabilities and risks explicit, and most of these decision support tools fail to incorporate drought information that could improve short- and long-term choices. As with other areas of climate risk management, dynamic adjustment to the climate in ranching operations would be enabled by better monitoring, data, forecasts, and analytical capacity. Such a suite of information and tools could lead to higher productivity during non-drought periods and lower financial and ecological impacts during droughts (Vaughan et al., 2016). However, this information needs to be widely available and easily incorporated into ranchers' decision-making at critical decisions points throughout each season.

3.2. Drought management strategies

At the center of dynamic ranch-drought decision-making is the choice of alternative responses and their expected outcomes. Agricultural extension services and drought management entities like the National Drought Mitigation Center (National Drought Mitigation Center, 2013) provide planning and decision tools aimed at this crux. We canvassed this literature, including extension advice and similar prescriptive publications and bulletins, to build a propositional inventory of drought adaptations on a western ranch (Table 2).

We have divided the many drought response strategies into four categories: (1) increasing the supply of forage to the herd; (2), decreasing the demand for forage; (3) financial risk management measures; and (4) long-term preparation measures (See the papers cited in Table 2 for more detail.).

The two main methods for increasing the supply of forage to the herd are purchasing feed and renting additional pasture (Eakin and Conley, 2002; Derner and Augustine, 2016). Purchasing feed creates a secondary source of forage, decreasing the overall stress on the rangeland. Renting additional pasture is a different means to the same end; livestock are moved to a secondary location to graze, allowing the demand for forage to be met while simultaneously lowering forage pressure on the rancher's rangeland (Eakin and Conley, 2002; Derner and Augustine, 2016). Both methods add to ranchers' operational costs, especially during times of drought when demand for additional forage and pasture is high, driving up prices.

Decreasing the demand for forage during drought is achieved chiefly through destocking – that is, selling cows, yearlings and calves to reduce the size of the herd (Eakin and Conley, 2002; Derner and Augustine, 2016; Wilmer et al., 2016). When forage production is likely to be decreased due to drought, reducing the overall herd size ensures that there is enough forage for a smaller herd, rather than keeping a large herd that would be stressed due to inadequate forage amounts for each cow. In extreme cases, this approach can involve liquidating the entire herd (Eakin and Conley, 2002; Coppock, 2011; Gill and Pinchak, 1999). The downside of this strategy is the potential for increased re-stocking costs, the loss of desirable genetics developed in the mother herd over the years, and the possible introduction of poor-performing animals. A second common method of reducing forage demand is to wean calves early by putting them on feed to reduce the nutritional demand on lactating mother cows and thus their demand for forage (Hart and Carpenter, 2005). Alternate financial measures primarily consist of seeking government aid and earning off-farm income (Nagler et al., 2007; Wilmer et al., 2016). Government drought relief programs act as a safety net, providing access to financial services or supplemental feed and water (Coppock, 2011). Drought relief programs are different from drought insurance programs, as these relief programs come into play during or after the drought, rather than before. Ranchers tend to diversify their income regardless of whether there is a drought underway, but this income risk diversification is an important tool for drought risk management (Coppock, 2011; Wilmer et al., 2016).

Long-term drought preparation can be separated into three primary categories – maintaining reserve forage, conservative stocking, and carrying drought insurance. Reserve forage entails holding land or feed that would not be used during normal years. Conservative stocking means grazing at intensities below the rangeland's theoretical carrying capacity (Derner and Augustine, 2016; Wilmer et al., 2016). There are two primary options for insurance: PRF (Pasture, Rangeland, and Forage) rain-index insurance program and the Noninsured Crop Disaster Assistance Program (NAP), both administered by the USDA. The PRF program is designed to provide acreage-based insurance coverage to rangeland, perennial pasture, or forage used to feed livestock in scenarios of low precipitation; the NAP program supplies financial aid to producers of otherwise non-insurable crops in the event of natural disasters that result in crop losses or lower crop yields (Johnson et al., 2015; USDA Risk Management Agency, 2015).

The most common methods of long-term drought adaptation are conservative stocking and purchasing additional feed (Macon et al., 2016). Many of the approaches laid out in the table require more proactive and agile planning. For example, only 60% of surveyed Wyoming ranchers have a current plan to address drought conditions (Kachergis et al., 2014). In the 1999–2004 drought, only 14% of Utah ranchers felt they were prepared (Coppock, 2011). Additionally, ranchers tend to use reactive drought management practices, instead of proactive measures (Derner and Augustine, 2016). A number of studies state that proactive drought planning is just as, if not more, important than reactive planning (Derner and Augustine, 2016; Kelley et al., 2016; Macon et al., 2016). However,

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[1] See, for example, the variety of spreadsheets available to ranchers from the Montana State University at http://www.montana.edu/softwaredownloads/livestockdownloads.html

Table 2
Drought response options.

Category	Specific Responses	References
Preparation Measures	Use conservative stocking rate	Bement (1969), Holechek et al. (1999), Smith and Waggoner (2005), Díaz-Solís et al. (2009), Coppock (2011), Paterson et al. (2012), Hancock et al. (2013), Kachergis et al. (2014), Thomas et al. (2015), Derner and Augustine (2016), Macon et al. (2016)
	Stockpile forage (grass banking)	Kachergis et al. (2014), Macon et al. (2016)
	Seek forecast information	Coppock (2011), Kachergis et al. (2014)
	Diversify livestock and plant species (agroforestry and mixed crop-livestock systems)	Wilmer et al. (2016), Rojas-Downing et al. (2017)
	Purchase insurance (feed, rain-index, etc)	Coppock (2011), Derner and Augustine (2016)
	Increase hay production	Coppock (2011)
	Change breeding strategy to improve cattle resilience	Scasta et al. (2016), Rojas-Downing et al. (2017)
	Avoid fully restocking after drought	Hart and Carpenter (1999), Wilmer et al. (2016)
	Rotate pasture and use shorter grazing periods	Eakin and Conley (2002), Kachergis et al. (2014)
Increase Supply of Forage to Herd	Use supplemental feed/hay and reduce feed waste	Eakin and Conley (2002), Nagler et al. (2007), Ritten et al. (2010a,b), Rasby and Niemeyer (2011), Paterson et al. (2012), Hancock et al. (2013), Kachergis et al. (2014), Derner and Augustine (2016)
	Rent additional pasture	Nagler et al. (2007), Kachergis et al. (2014), Derner and Augustine (2016)
	Strategically place salt, mineral, water, etc. to distribute grazing pressure evenly	Hart and Carpenter (1999)
	Move cattle to a feedlot	Kachergis et al. (2014)
Decrease Demand for Forage	Reduce herd size (destocking)	Buxton and Smith (1996), Eakin and Conley (2002), Coppock (2011), Kachergis et al. (2014), Derner and Augustine (2016), Wilmer et al. (2016), Gill and Pinchak (1999)
	Wean calves early	Eakin and Conley (2002), Nagler et al. (2007), Paterson et al. (2012), Hancock et al. (2013), Kachergis et al. (2014), Johnson et al. (2015), Derner and Augustine (2016)
	Maintain yearlings for quick sale upon onset of drought	Hart and Carpenter, 1999, Nagler et al. (2007), Smith (2007), Torell et al. (2010), Kachergis et al. (2014), Derner and Augustine (2016)
	Ammoniate crop residues for improved digestibility and intake	Paterson et al. (2012)
	Match cattle to forage resources based on size and milk production potential	Scasta et al. (2016)
Alternate Financial Measures	Seek government aid	Eakin and Conley (2002), Nagler et al. (2007), Kachergis et al. (2014), Derner and Augustine (2016)
	Diversify sources of income	Kachergis et al. (2014)
	Grow alternative crops	Nagler et al. (2007)
	Use income averaging and tax relief for sale of breeding livestock	Tronstad and Feuz (2002), Schroeder and Ehmke (2008)
	Renegotiate bank loans	Coppock (2011)
	Use forward contracting for livestock sales and hay purchase	Coppock (2011)

as discussed earlier, uncertainty about even near-term future drought conditions, such as the spatial extent, intensity, and duration hinder proactive drought planning (Kelley et al., 2016). Additionally, drought assistance or relief programs further discourage proactive planning, as these programs may encourage ranchers to take risks, acting as a “fail-safe” for any poor decisions made (Dunn et al., 2005; Kelley et al., 2016).

3.3. Information: key to drought decision-making

Proactive drought response requires accurate and timely information. There are major costs to implementing drought adaptation plans if the drought does not materialize. Many drought response measures, such as selling part of the breeding herd or renting additional pasture, are irreversible investments. Without adequate lead-time for drought warnings and timely monitoring and analysis of evolving conditions, producers may not be able to respond in time even if the information is accurate. There was no early warning of the massive 2012 drought despite the availability of many of the drought indices we have today (Hoerling et al., 2012), highlighting the need for improvements in this area.

Drought early warning systems are still under development in most drought-prone regions of the world (Pulwarty and Sivakumar, 2014) and in the U.S. (Svoboda et al., 2002). At present, there exist numerous drought monitors that describe current conditions across the U.S., some indices of present conditions that act as leading indicators of future drought, and a few actual forecast products. At this point in the development of early warning systems, most available products involve monitoring and detection of current conditions rather than forecasting future conditions. Yet even monitoring information must be analyzed and provided to users in a timely fashion to be useful to a rancher’s drought response. Additionally, the frequency and magnitude of droughts in the western

U.S. may change in the future due to climate change (Polley et al., 2013a; Ault et al., 2014), which adds another layer of uncertainty to drought information and warning systems.

3.3.1. Drought monitors

Drought is defined, generally, by a deficit in water availability, at some threshold duration and severity, but also by the Earth and human systems that are impacted (e.g. agricultural drought, hydrological drought, etc.). Currently, no singular index paints a full picture of these impacts (Knutson and Fuchs, 2016). Because of the multi-faceted nature of drought, different indices provide information on different aspects of drought. Most indices use temperature and precipitation to assess the physical severity of drought (McEvoy et al., 2016). The Palmer Drought Severity Index (PDSI) and its variants were the dominant sources of drought conditions in the U.S. for decades following its creation in 1965. Around 2000, the National Integrated Drought Information System (NIDIS) introduced its key assessment product, the U.S. Drought Monitor (USDM), which is now widely used (Svoboda et al., 2002). The USDM is a weekly map that uses the PDSI along with several other indicators and qualitative assessments from local experts to depict drought severity ranging from abnormal to exceptionally dry.

The PDSI estimates soil moisture from temperature and precipitation, but more extensive in situ and modeled soil moisture measures like the Standardized Soil Moisture Index (SSI) are increasingly available to reveal this key factor (AghaKouchak, 2012). Recently launched satellites monitor soil moisture levels at a far wider scale than was previously feasible. For example, the Gravity Recovery and Climate Experiment (GRACE) (Houborg et al., 2012) satellite pair, launched in 2002, provide data on Total Water Storage (TWS) on the Earth's surface. This is done by detecting minute changes in gravity on the Earth's surface via micron-scale measurements of the distance between the satellites. GRACE observations of TWS can then be used to infer smaller scale water storage variations, including soil moisture at varying depths. Differentiation of surface, root zone, and groundwater moisture make such measurements especially useful tools for monitoring agricultural drought. The Soil Moisture Active Passive (SMAP) satellite, launched in 2015, produces daily, gridded soil moisture at different depths using microwave radiation (Velpuri et al., 2016). While soil moisture level is an indicator of current drought, it can also serve as a leading indicator of forage-relevant drought (AghaKouchak, 2012).

Another relevant index, the Vegetation Drought Response Index (VegDRI), incorporates many different sources of information into a singular index that monitors and characterizes vegetation stress due to drought. VegDRI is a collaborative effort between the United States Geological Survey's Center for Earth Resources Observation Sciences (USGS-EROS) and the National Drought Mitigation Center (NDMC). It utilizes a regression-tree data mining technique applied to other drought indices such as the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI), ocean temperature information from models such as the Southern Oscillation Index (SOI), general vegetation presence and health information from satellite-derived Normalized Difference Vegetation Indices (NDVIs), as well as land use/land cover information and ecological information such as soil and ecosystem type from a variety of sources. This yields a 1-km resolution, bi-weekly gridded index of vegetation stress due to dry conditions during the growing season. It is important to distinguish VegDRI from an NDVI. NDVIs are incorporated into the VegDRI, but the NDVIs capture vegetation stress from any environmental factor (disease, flooding, pests, drought, etc.) while VegDRI depicts vegetative stress due to drought alone. The index is also separated into rangeland and cropland layers which can help isolate impacts and focus the response process.

3.3.2. Leading indicators of drought

In the information space between these detection products and forecasts are leading indicators, typified by the new Evaporative Demand Drought Index (EDDI). The EDDI is a multi-scalar model, meaning that it can be calculated using different time windows for different purposes. For instance, shorter time resolutions are useful for detection of rapidly developing drought. EDDI uses the relationship between current evapotranspiration (ET) and evaporative demand (E_0) to indicate the likely emergence of drought. If ET is observed to fall while E_0 rises, EDDI would anticipate a longer-term drought. If the relationship is parallel, whereby ET and E_0 rise together, a quickly developing "flash drought" may be forming (Hobbins et al., 2016). In a comparison of predictive capacity, the EDDI was shown to indicate coming drought conditions well before, sometimes months before, the USDM, SSI, SPI (Standardized Precipitation Index), and the ESI (Evaporative Stress Index) (McEvoy et al., 2016). This sort of product may have been useful in the 2012 drought that, just months before it deepened dramatically, was not indicated in monitoring nor seasonal drought outlooks (Hoerling et al., 2012; Hobbins et al., 2016). Though EDDI is still in an experimental stage, it is now available to the public.

3.3.3. Drought forecasts

Some forecasts are derived mostly by extrapolating current conditions. For example, streamflow forecasts in the West are based mostly on current snowpack. Future runoff from the snowpack is extrapolated by empirical and simulation models. Seasonal and short-term forecasts may be used to tilt the runoff predictions, but the main factor is the measured snowpack at key points in the accumulation season.

The long-term nature of drought means that prediction per se requires forecasting atmospheric conditions weeks to months in advance. Current weather forecasts are limited to short time horizons, so monthly and seasonal outlooks are left to fill that role. Currently in the U.S., drought monitoring and diagnostics are extended to forecasts through the application of long-range (6–14 days) temperature and precipitation forecasts from the National Weather Service (NWS) and 1- to 3-month outlooks from the Climate Prediction Center (CPC) (Fig. 3). These forecasts are translated into the Monthly and Seasonal Drought Outlook (MDO and SDO). The SDO uses the USDM map as a base and projects drought trends as either developing, persisting, improving, or ending for the next 30- to 90-day period.

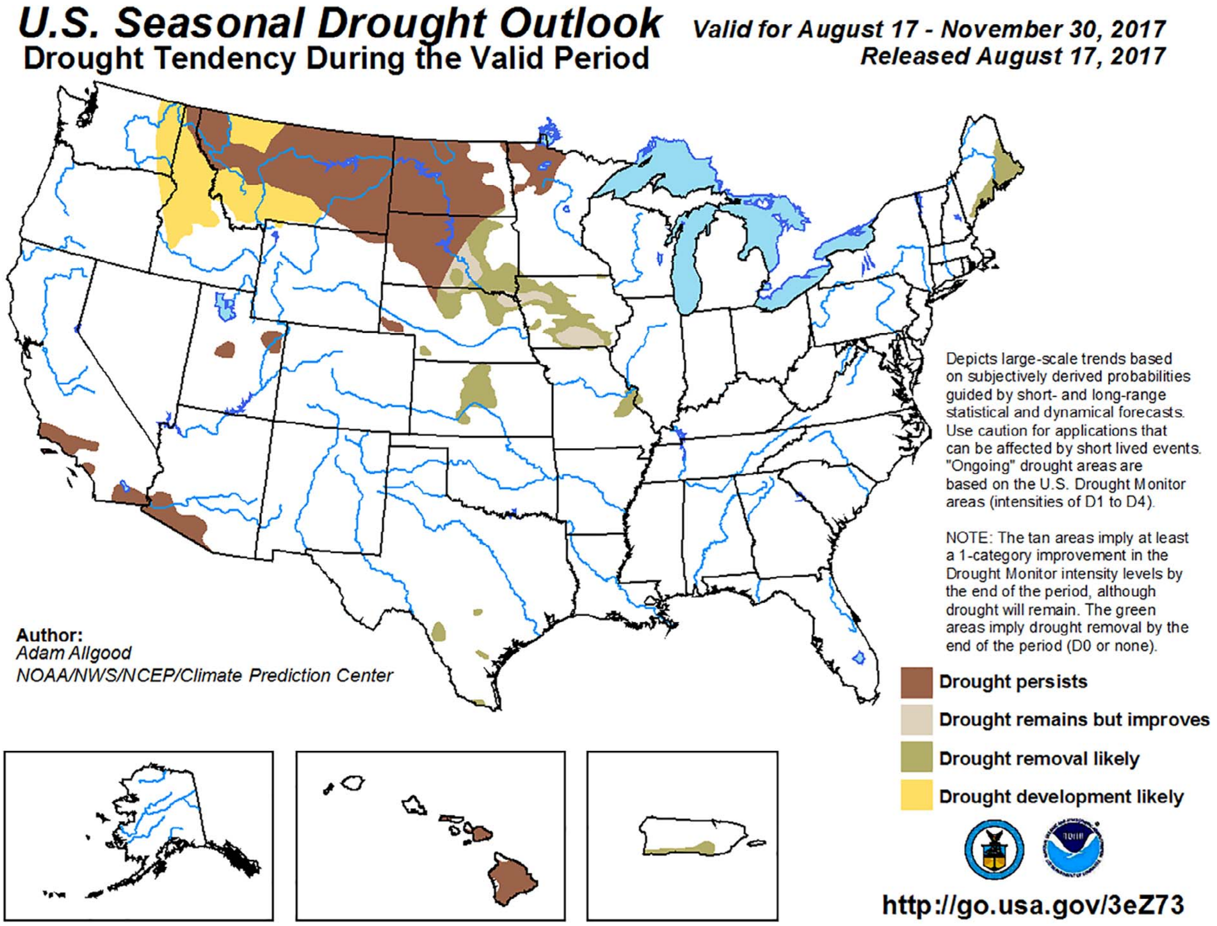

Fig. 3. The Seasonal Drought Outlook. Source:http://www.cpc.ncep.noaa.gov/products/expert_assessment/sdo_summary.php.

Overall, seasonal forecasts, and specifically drought forecasts, offer limited or no skill (Hoerling et al., 2012). Verification scores for seasonal outlooks show pockets of skill above chance in projecting temperature anomalies for parts of the western U.S., especially the Southwest where the El Niño/La Niña signal is strongest (Crimmins and McClaran, 2015), and no or even negative skill for precipitation across the country.[2] This lack of seasonal forecast skill limits the skill of the SDO (NOAA, 2015). The SDO achieves limited skill (about 10 percent above chance) at forecasting drought persistence in areas where the USDM observes current drought, but has little skill at forecasting new drought development, as observed by Hoerling et al. (2012).

3.3.4. Future prospects

Substantial research is underway on stochastic and deterministic seasonal forecasting, and assessments of this effort over the last few decades evince limited progress and a great deal of anticipation (Murphy et al., 2001; Weisheimer and Palmer, 2013). At this writing, there is even a monthly (3–6 week) western U.S. forecast contest underway, aptly called a forecast rodeo, with sizeable cash prizes.[3] Some recent progress came from bridging weather forecast and climate models (Barnston et al., 2010), especially using multi-model ensembles (Hagedorn et al., 2005). The resulting seasonal forecasts of temperature and precipitation provide ingredients to forecast drought, but predicting extremes, the tails of temperature and precipitation distributions that cause the severe droughts that impact ranchers the most, is inherently more difficult than predicting typical conditions (Barnston and Mason, 2011). Progress may arise from systems that merge monitoring with forecasting. The Global Integrated Drought Monitoring and Prediction System (GIDMaPS) predicts drought conditions with 1 to 6-month lead time using a combination of satellite and model-derived atmospheric and soil moisture data along with two existing drought indices and one newly developed multivariate index (Hao et al., 2014). Chikamoto et al. (2017) provides another recent example using the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM). This model incorporates data associated with various sea-surface temperature oscillations, such as the ENSO, the Pacific-Decadal Oscillation, and the Atlantic/Pacific Sea Surface Temperature Contrast, along with Earth system models

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[2] Available from: http://www.cpc.ncep.noaa.gov/products/verification/summary/index.php?page=map

[3] See: https://www.drought.gov/drought/sub-seasonal-climate-forecast-rodeo

and predictions of anthropogenic forcing to produce drought and wildfire predictions with 10- to 45-month lead times in the Southwest US. The model successfully predicted cessation of multi-year drought conditions in Southern California, which had outlasted significant droughts in Central, Southeast and Northwest U.S. If this methodology proves skillful over time, it could represent a significant advance over the monthly to seasonal outlooks included in the CPC's SDO (Chikamoto et al., 2017). ENSO signals have also been used to predict precipitation and drought in other countries, such as Africa and Australia. (Funk et al., 2014; Nicholls, 1989).

The National Academy of Sciences report, "Weather Services for the Nation: Becoming Second to None," challenged the country's weather and climate research institutions to address some of the current climate forecast limitations outlined above (National Research Council, 2012). One attempt is the National Water Model (NWM), which came online in August of 2016 with the goal of improving prediction of hydrologic events in the US. Using data from 8,000 USGS stream gauges and newer data sources such as the GRACE and SMAP satellite missions (Antonio et al., 2017). The NWM is not focused solely on drought, but instead aims to capture as much of the water-cycle in North America as possible to best predict water-based events (United States Senate Appropriations Subcommittee on Commerce Justice and Science, 2016).

If drought predictions improve in the future, the challenge, as with all seasonal forecasts, will become making them usable for decision makers (National Research Council, 1999). For ranchers, that means translating seasonal temperature and precipitation, or drought index forecasts into estimates of forage production. Grassland models that use temperature and precipitation as inputs (such as those reviewed in Section 2.1.1) can logically be used to predict future forage. But the use of forecast products has been minimal in the ranching community because summer forecast reliability is lacking. Crimmins and McClaran (2015) report that ranchers and forest service managers in Arizona want forecasts that are at least 70% accurate before they are willing to use them to make potentially costly adaptation decisions. The authors conclude that only the most risk-tolerant ranch managers will give significant weight to drought predictions, and only about 25% of ranchers they surveyed are satisfied with currently available drought information and forecasts (Crimmins and McClaran, 2015). A survey of Wyoming ranchers showed that only 16% utilized forecasts to help plan stocking rate adjustments (Kachergis et al., 2014).

The low rates of climate information utilization and the many climate-sensitive decisions described in this review paper suggest a large unmet need for usable, reliable drought monitoring and forecast information. There are many possible reasons why such a small portion of ranchers use monitoring information and forecasts to manage drought. For example, the information may not be reliable or specific to their rangeland, it may not be easy to access or understand leaving them with high search costs and the stress of difficult information processing, or they may wish to avoid or delay irreversible investments under uncertainty. The question of how the available information is used and how it can be better communicated needs to be further investigated so we can better understand the value of these climate information products and how to increase their usability.

4. Climate change, drought, and ranching

Growing evidence indicates that climate change may increase aridity and drought. The value of drought monitoring and forecast information should increase if climate change increases the frequency and/or magnitude of western droughts (Ault et al., 2014). The global climate has already warmed 0.85 °C over the last century (Intergovernmental Panel on Climate Change, 2013). Observations show warming over much of the American West in both winter and summer, with mixed signals for precipitation (Polley et al., 2013b). In the Northern Great Plains, average daily temperatures are predicted to rise 2.2–3.3 °C by 2050 (Derner et al., 2017). In the American Southwest and the Great Plains, increased temperatures will likely increase aridity (Hoerling et al., 2012). This predicted increase in aridity could lead to more frequent or more severe drought (Houérou, 1996). Even regions that see no decrease in precipitation may experience worsened drought due to higher evapotranspiration demand that arises from higher temperatures (Cook et al., 2015; Woodhouse et al., 2016).

However, the potential for increased drought risk is juxtaposed with possible benefits of climate change in some regions. Rangelands in the Northern Great Plains may benefit from longer growing seasons and may even see precipitation increases that counteract the drying effects of warmer temperatures (Derner et al., 2017).

Overall, how climate change affects drought management on the ranch will also depend on whether changes in precipitation outweigh or exacerbate increases in water demand from increased temperatures. Changes in different drought dimensions – severity, frequency, and duration – evoke different adaptive responses. Increased drought duration, predicted by some global warming models (Ault et al., 2014), may be especially worrisome as multi-year droughts eventually overwhelm many of the coping mechanisms currently available to ranchers. Better monitoring and projection of the effect of climate change on precipitation would help ranchers better adapt to drought in a changing climate.

5. Conclusions

Ranching is a dynamic socio-ecological system that must adapt to climate variability. Drought, especially if widespread, sets off a chain of ecological and economic effects within the system. Ranchers handle these climate risks in several ways. They diversify their operations, purchase insurance, and make short-term drought adaptation investments like buying extra feed or seeking additional pasturage. Over the long term they may stock conservatively, so there is sufficient forage for the herd even when rainfall drops, or they can stock at higher rates but be ready to adapt quickly to periods of drought by reducing forage demand (e.g., by destocking) or increasing forage supply (e.g., by buying supplemental feed). The conservative stocking strategy may be optimal on arid ranges (Thomas et al., 2015) and when information about drought is either not available or costly to obtain. Full carrying capacity stocking with agile adaptation may be optimal if climate information is readily available and easily incorporated into ranchers' production strategies.

The key climate risk management challenge in ranching is making timely decisions while a slow-onset drought unfolds. To meet this challenge, ranchers need accurate assessments of drought conditions as they develop. In reviewing ranching decision structures and the current availability of drought information necessary to make adaptation investments by crucial decision points in the season, we conclude that drought forecasts, due to their limited skill (Hoerling et al., 2012), are not as useful to ranchers as highly accurate information about current drought conditions. Because drought adaptation investments are often irreversible, ranchers are hesitant to deviate from their normal practices based on information that is highly unreliable. Compared to low-skill forecasts of future conditions, a precise understanding of the current state of drought may be far more valuable. Ranchers already rely on the US Drought Monitor that gives a coarse assessment of drought conditions across the U.S. However, new measures of soil moisture like the Standardized Soil Moisture Index (SSI), the Soil Moisture Active Passive (SMAP) satellite, and the Vegetation Drought Response Index (VegDRI), as well as the Evaporative Demand Drought Index (EDDI) can provide clear information about current conditions on their ranches that serve as leading indicators for drought. While ranchers are especially interested in drought conditions on their ranches, they also can use information on drought conditions in other regions so that they can judge how other ranchers and thus cattle markets will respond.

Further research is needed to understand existing barriers that may prevent ranchers from using the available information. Studying how climate information is used and how it can be better communicated to be more usable in key climate risk decisions will help us understand the value of these climate information products and improve climate risk management by decisionmakers.

The questions that arise for drought risk management in the ranching industry are relevant to other areas of climate risk management and decision and risk theory. Flooding is another low frequency, high-risk event that is difficult to predict with much lead time. Similar anomalies appear in the demand for flood insurance that we see in the demand for crop and ranching insurance (Kunreuther, 1996; Hogarth and Kunreuther, 1989; Coble and Barnett, 2012; Karlan et al., 2014; Du et al., 2016). Exploring how ranchers respond to climate risk and how they incorporate information into their risk management decisions can generate new insights into climate risk management at the governmental, business, and household level.

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