Climatic Change
DOI 10.1007/s10584-017-2029-6

Vulnerability of grazing and confined livestock in the Northern Great Plains to projected mid- and late-twenty-first century climate

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Received: 28 November 2016 / Accepted: 7 July 2017
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Abstract The Northern Great Plains (NGP) region of the USA—which comprises Montana, Wyoming, Colorado, North Dakota, South Dakota, and Nebraska—is a largely rural area that provides numerous ecosystem services, including livestock products, cultural services, and conservation of biological diversity. The region contains 25% of the Nation's beef cattle and approximately one-third of the confined beef cattle, as well as the largest remaining native prairie in the US—the Northern Mixedgrass Prairie. With rising atmospheric CO_2, the NGP is projected to experience warmer and longer growing seasons, greater climatic variability, and

This article is part of a Special Issue on "Vulnerability Assessment of US Agriculture and Forests developed by the USDA Climate Hubs" edited by Jerry L. Hatfield, Rachel Steele, Beatrice van Horne, and William Gould.

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Published online: 24 July 2017

more extreme events (e.g., increased occurrence of large precipitation events). These climatic changes may affect livestock production both directly via physiological impacts on animals and indirectly via modifications to forage, invasion of undesirable plants, and increased exposure to parasites. This raises concerns about the vulnerability of grazing livestock operations and confined livestock operations to projected changes in mid- (2050) and late- (2085) twenty-first century climate. Our objectives are to (1) describe the NGP's exposure to temperature and precipitation trends, inter-annual variability, and extreme events; (2) evaluate the sensitivity of beef cattle production to direct and indirect effects imposed by these projected climatic changes; and (3) provide a typology of adaptation strategies to minimize adverse consequences of projected changes and maximize beneficial consequences. Agricultural managers have developed considerable adaptive capacity to contend with environmental and economic variability. However, projected climatic changes, especially the increased frequency and magnitude of weather extremes, will require even greater adaptive capacity to maintain viable production systems. Consequently, regional vulnerability to projected climatic changes will be determined not only by ecological responses but also by the adaptive capacity of

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individual managers. Adaptive capacity in the NGP will differ from other regions, in part because projections suggest some opportunities for increased livestock production. Adaptations in both grazing and confined beef cattle systems will require enhanced decision-making skills capable of integrating biophysical, social, and economic considerations. Social learning networks that support integration of experimental and experiential knowledge—such as lessons learned from early adopters and involvement with science-based organizations—can help enhance decision-making and climate adaptation planning. Many adaptations have already been implemented by a subset of producers in this region, providing opportunities for assessment, further development, and greater adoption. Context-specific decision-making can also be enhanced through science-management partnerships, which aim to build adaptive capacity that recognizes multiple production and conservation/environmental goals.

1 Introduction

The Northern Great Plains (NGP) of the USA is an important agricultural and ecological region encompassing Montana, Wyoming, Colorado, North Dakota, South Dakota, and Nebraska. This region has 25% of the nation's beef cows, sheep, and lambs (NASS 2012), 34% of the nation's cattle on feed (NASS 2012), and significant numbers of dairy cattle and hogs. It is therefore of critical importance to national and international food security. Agricultural producers manage more than one-third of the USA's 140 million ha of pasture and rangeland, including the largest remaining tract of native rangeland in North America—the Northern Mixedgrass Prairie. This region is projected to have rising atmospheric CO_2, warming surface temperatures, longer growing seasons (Badeck et al. 2004), increased weather variability, and more extreme events (e.g., deluges, longer and more severe droughts) (Nardone et al. 2010). This raises the question "How vulnerable are livestock producers to climatic changes and extreme weather events that exceed those experienced in the past?"

Vulnerability describes the degree to which a system is likely to experience harm due to exposure to a hazard (i.e., a disturbance or stressor). Vulnerability consists of three interrelated components—exposure, sensitivity, and adaptive capacity (Adger 2006). In the context of climatic changes, exposure refers to the direct effects of warming, modified precipitation regimes, a greater frequency and intensity of extreme weather events, and increased weather variability (Troy et al. 2015) on the agricultural sector and ecological processes (Hamilton et al. 2016). Exposure also involves indirect effects of climatic change, such as expansion of invasive plants, increasing wildfires, and increased incidence of pathogens and parasites; for the NGP region, this also includes the threat involving land-use change from pasture and rangeland to cropland and cropping system changes (e.g., Wright and Wimberly 2013; Lark et al. 2015; Rashford et al. 2016). Sensitivity describes the magnitude of impact on systems, both ecological and economic, following exposure to hazards or stressors. The NGP region is unique relative to much of the USA in that it is experiencing both beneficial and detrimental consequences of climate change (Briske et al. 2015). For example, warmer winters will reduce the duration of supplemental livestock feeding provided that there is forage carryover from the current growing season available to graze during the dormant season. Rising atmospheric CO_2, plus warming, will increase pasture and rangeland productivity (Mueller et al. 2016) though forage quality (e.g., nitrogen, N, content may decline (Milchunas et al. 2005) and invasive plants increase in abundance and competitive ability (Blumenthal et al. 2013, 2016). Collectively, these changes are likely to increase the capacity for livestock production. Lastly,

adaptive capacity—the ability of humans to anticipate and respond to potential or actual exposure to various stressors (Adger 2006)—is an essential component of agriculture vulnerability because it establishes the foundation upon which adaptation strategies are conceptualized, implemented, and evaluated (Vincent 2007, Nelson et al. 2010). Yet change of any kind is difficult, so the development, adoption, and implementation of climate change adaptations pose challenges for both grazing and confined livestock operations (Joyce et al. 2013; Briske et al. 2015).

The goal of this paper is to assess the vulnerability of livestock grazing systems and confined livestock operations in the NGP to projected climate conditions for the mid- (2050) and late- (2085) twenty-first century. Precipitation and temperature, including their intra- and inter-annual variability, are the primary climate variables that influence grazing lands and livestock (Polley et al. 2013). Our specific objectives are to (1) describe the NGP's exposure to projected temperatures and precipitation, (2) evaluate the sensitivity of beef cattle production to direct and indirect consequences of the projected climatic conditions, and (3) provide a typology of adaptation strategies to optimize the benefits and minimize the adverse consequences of climatic changes.

2 Exposure—predicted climatic conditions for mid- (2050) and late- (2085) twenty-first century

2.1 Temperature

Across the NGP, daily average temperatures are projected to increase 2.2–3.3 °C by 2050, with an increase of 4.4–6.7 °C by 2085. Annual 5-day maximum temperatures are predicted to increase 3.3–4.4 °C by 2050, relative to the reference period of 1976–2005 ("Downscaled CMIP5 Climate and Hydrology Projections" archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/, Pierce et al. 2014, 2015). Maximum temperatures are expected to continue rising through 2085, with 5.6 °C increases south of the South Dakota-Nebraska border and 6.7 °C increases further north. Number of days with maximum temperature exceeding 35 °C is projected to increase by 20–40 days across the region by 2050. By 2085, a further increase of 20 additional days with maximum temperatures exceeding 35 °C is projected.

Concomitantly, annual 5-day minimum temperatures are projected to increase 2.2 °C in the southwestern part of the NGP, and 5.6 °C in the northeastern part of the NGP by 2050. This geographical trend continues through 2085 with the magnitude of warming doubling to 4.4 °C in the southwest and an 8.9 °C increase in the northeast. The number of days where the minimum temperature is less than 0 °C (freezing) decreases by 20–40 days in 2050, and by 50–70 days in 2085. Higher minimum temperatures are expected to both harm and help livestock production. They will, for example, increase the abundance of some parasites and pathogens (as discussed later). However, they will also markedly reduce livestock producers' winter feed costs—often the largest production expense (McCartney et al. 2004). The net effect of warming on livestock production is a complex function of many direct and indirect impacts, whose relative magnitudes will vary throughout the NGP.

2.2 Precipitation

A majority of the NGP is projected to experience a 100% increase in 5.1-cm rainfall events by 2050, with this trend continuing through 2085 ("Downscaled CMIP5 Climate and Hydrology

Projections" archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/, Pierce et al. 2014, 2015). The probability of rainfall events exceeding 7.6 cm increases 100% in the eastern 1/3 of the region—areas predominantly east of the 100th meridian—for both 2050 and 2085. Maximum 1-day precipitation is projected to increase 10–30% by 2050, and 15–40% by 2085. The annual longest consecutive dry-day period in the NGP is projected to remain similar to the reference period (1976–2005), or even 3 days shorter, in both mid- and late-twenty-first century. This projection is unique among the geographical regions of the USA.

3 Sensitivity of livestock production

3.1 Forage quantity and quality

The primary outcomes of climate change—rising atmospheric CO_2 concentration, atmospheric warming, and modified amounts and temporal patterns of precipitation—affect soil-water availability and therefore many aspects of livestock production and rangeland function (Izaurralde et al. 2011; Polley et al. 2013). Livestock production will be affected both directly, via physiological impacts on animal performance, and indirectly via modifications to forage composition, quantity and quality, and ectoparasite dynamics (Polley et al. 2013).

Forage production, according to modeled responses of NGP vegetation, is likely to increase about 5–10% by 2050 in response to increasing minimum annual temperatures and CO_2 enrichment (Reeves et al. 2014). Total plant production in the Northern Mixedgrass Prairie is consistently increased by experimental atmospheric CO_2 enrichment and warming. This is especially true in dry years, due to CO_2-induced increases in plant water-use efficiency (Mueller et al. 2016).

Forage availability is a function of multiple interacting variables that may vary in importance throughout the growing season. Warmer temperatures will hasten spring green-up, as well as peak forage availability in the summer, but also allow growth later into the fall (Reyes-Fox et al. 2014). An earlier peak in forage availability will be due, in part, to decreased abundance of C_4 grasses (by more than 50%) (Mueller et al. 2016). An equivalent increase is projected, though, for more productive C_3 grasses (Mueller et al. 2016). Late-season growth can be extended through more efficient plant water-use under dry conditions and elevated CO_2 (Reyes-Fox et al. 2014). Earlier vegetation green-up may provide opportunities for grazing livestock operations to calve earlier in the calendar year to better match cow nutrient demand with nutritive quality of forage (Stockton et al. 2007).

Forage quality, like forage availability, is a complex function of multiple factors. For example, although larger individual precipitation events could increase plant productivity by increasing soil-water storage (Heisler-White et al. 2009), forage quality such as plant N content may decline (Milchunas et al. 2005). A recent meta-analysis of CO_2 effects on forage quality reveals that elevated atmospheric CO_2 increases total non-structural carbohydrates by an average of 25%, but decreases forage N content by 8% (Dumont et al. 2015). However, regional effects of elevated CO_2 can vary, with relatively large declines in both forage N and in vitro digestibility demonstrated in the NGP's semiarid rangelands (Milchunas et al. 2005; Mueller et al. 2016). Unlike elevated CO_2, warming has no consistent effects on carbohydrates or N content of plants (Dumont et al. 2015). In light of CO_2 and warming effects, forage N will likely remain sufficient to meet maintenance requirements of mature livestock (approximately 1% N), but values less than 1.5% will be more common under future climates (Milchunas et al.

2005, Mueller et al. 2016), which could suppress ruminant growth rates and reproduction. Adverse effects of low nutritive value of forage can be offset by monitoring temporal fluctuations in diet quality, providing animals with N supplements, shifting some stored-forage use to late fall, and inter-seeding pastures with legumes (Mortenson et al. 2005; Tolleson and Schafer 2014).

Invasive plants may also become more problematic due to changes in the amount and timing of plant resource availability. For example, elevated CO_2 facilitates *Linaria dalmatica* (Dalmatian toadflax) invasion by increasing the availability of water and carbon (Blumenthal et al. 2013). Warming more than triples seed production of *Bromus tectorum* (cheatgrass) by increasing its growth during the fall and spring (Blumenthal et al. 2016). Biogeographic models for the NGP suggest that several problematic invaders (including *B. tectorum*) will become more abundant, but some others (e.g., *Euphorbia esula* (leafy spurge)) will become less abundant (Bradley et al. 2009). Management of invasive species that thrive under projected climatic conditions will be challenging, but advances in our understanding of the mechanisms that facilitate invasion can help guide adaptation, including more effective use of targeted grazing (Frost et al. 2012), monitoring and suppression in areas of likely expansion, and adaptive timing of grazing to encourage competitive forage species (Rinella and Bellows 2015). For example, producers could turn out their livestock earlier to reduce the competitive ability of invasive plants that grow most vigorously in early spring (Rinella and Bellows 2015).

3.2 Animal heat stress

Air temperature is the most important climatic variable contributing to an animal's thermal environment, but humidity, wind speed, solar radiation, and nighttime temperature minimums all have significant effects on livestock heat stress in all types of animal facilities (Mader et al. 2006). Economic losses from heat stress originate from three primary responses: (1) decreased performance (e.g., less feed intake, lowered feed efficiency), (2) decreased reproduction, and (3) increased mortality (St-Pierre et al. 2003). These losses are greatest when animals are confined outdoors in a limited space. For example, feedlot cattle will be responsible for 15–20% of the estimated annual economic losses for all livestock species due to heat stress (St-Pierre et al. 2003). Effects of heat stress can be reduced by providing animals with naturally ventilated buildings or shade structures, to protect them from solar radiation, or with mechanically ventilated buildings to protect them from both solar radiation and unreliable wind speeds (Brown-Brandl et al. 2013).

3.3 Parasites and pathogens

Earlier spring warming and greater maximum temperatures will potentially escalate ectoparasite exposure (Scasta et al. 2017). For example, face fly (*Musca autumnalis*) and horn fly (*Haematobia irritans*) emergence can be predicted using accumulated degree-day thresholds of 70 days at 12 °C or above (Krafsur and Moon 1997) and 10.5 days of 25 °C or above (Lysyk 1999), respectively. Projected precipitation changes, coupled with temperature changes, will lead to greater parasite egg and pupae survival, shorter dormancy periods, greater physical activity of parasites, and longer periods of animal exposure (Goulson et al. 2005). Species such as horn flies and biting midges (*Culicoides* spp., a vector of bluetongue virus), which have historically been restricted to lower elevations, may be able to expand their elevational range upward, resulting in more livestock in the NGP being exposed (Scasta

2015). Similarly, warmer winters coupled with longer and wetter growing seasons may lead to greater infestation and expansion of ticks, especially into northern latitudes and higher altitudes (Dantas-Torres 2015).

Effects of projected climate change on endoparasites of livestock (e.g., roundworms) are less clear due to seasonal and species variability. For example, an increase in *Haemonchus contortus* and *Teladorsagia circumcincta* infection pressure is expected in small ruminants due to accelerated parasite development in winter months. In contrast, a decrease in infection pressure of *Ostertagia ostertagi* in cattle is expected due to greater parasite mortality from higher temperatures (Rose et al. 2015). Effects of climate change on viral diseases (e.g., bovine viral diarrhea), protozoan pathogens (*Neospora caninum*), and bacterial infections (e.g., *Brucella* spp., *Bacillus anthracis, Escherichia coli*) are even less understood (Hoberg et al. 2008). One hypothesized impact is that changing temperatures and precipitation will affect pathogen persistence in the environment, and hence livestock exposure. Similarly, changes in the spatio-temporal distribution of domestic versus wild ungulates may affect the emergence and transmission of pathogens within and between species (Hoberg et al. 2008).

3.4 Riparian structure and function

Peak streamflow from snowmelt in the NGP has traditionally occurred during April–July, but is now occurring 1–2 weeks earlier due to increased temperatures (Ryberg et al. 2016). With future warming, timing of snowmelt and peak flows will continue to advance. Extreme rainfall events, which are predicted to double in the next 35 years, will increase stream velocity. In turn, stress on stream beds and banks will escalate, resulting in increased erosion potential via scouring and downcutting. These impacts are expected to be worse on streams with confined floodplains, steep gradients, or fine channel material (alluvial and lacustrine) (Bear et al. 2012).

Stream banks can be stabilized with desirable riparian vegetation, which dissipates energy of flood waters, increases trapping of sediments in its extensive root system, and ultimately decreases erosion (Gregory et al. 1991; Shafroth et al. 2002). Maintaining native, riparian vegetation through management of grazing (timing, intensity, and duration) can also increase infiltration and minimize changes to flood regimes and stream temperatures (Chambers et al. 2012). In contrast, invasive species such as shallow-rooted Kentucky bluegrass (*Poa pratensis*) and smooth bromegrass (*B. inermis*)—which are more competitive under projected climatic conditions—could negatively affect bank stability and channel morphology (Gregory et al. 1991). Targeted grazing can reduce non-native species within riparian vegetation while increasing deep-rooted grass and sedge species (Evans et al. 2004). Development of off-stream water and shade can prevent livestock from concentrating in riparian areas, thereby decreasing the potential for bank erosion (Grudzinski et al. 2016). The use of genetic selection or development of new cattle breeds that are genetically predisposed to graze uplands or slopes of rugged terrain is another adaptation strategy to reduce impacts on riparian vegetation (Bailey et al. 2015).

4 Adaptive capacity and climate risk management in livestock systems

Livestock managers have developed considerable adaptive capacity to contend with both environmental and economic variability. However, projected increases in the frequency and magnitude of climatic extremes will require even greater adaptive capacity to maintain viable

livestock production systems (Howden et al. 2007; Joyce et al. 2013). Adaptations can include incremental adjustments, which maintain viability of current production enterprises through added performance margins, technical improvements, shortened planning horizons, and no-regret adaptations that make sense in a range of future conditions (Hallegatte 2009). Alternatively, adaptations can transform the system in more fundamental ways, for example, by altering an operation's scale, goals, or location (Kates et al. 2012; Rickards and Howden 2012). Adaptation is an iterative risk-management strategy that involves learning and adjusting, rather than adhering to a prescribed set of technologies or policies (Nelson et al. 2007; Joyce et al. 2013). It requires careful assessment of the feasibility of current management under climatic changes, and frequent evaluation of the effectiveness of adaptations under changing climate.

A region's vulnerability to climatic change will be determined not only by ecological responses but also by the adaptive capacity of individual managers. Strategic-thinking skills and social capital may be more important to the success of adaptation planning than technical capability or considerations (Marshall 2010). Managers with limited social, economic, or environmental flexibility are especially vulnerable to weather variation (Marshall 2010), and likely to climatic change as well. Vulnerability has also been correlated with strong place and livelihood attachment, and a reluctance to diversify livestock operations, particularly among aging, independent managers (Marshall 2010; Marshall and Smajgl 2013). Income and size of a livestock production enterprise positively influence the adoption of innovative practices. For example, managers with larger properties tend to implement a greater number of management practices to increase enterprise flexibility and lessen the impacts of drought (Kachergis et al. 2014). Adaptive capacity clearly varies among managers; they have diverse levels of emotional and financial flexibility, interest in adapting to climatic change, capacity to manage risk, and ability to plan, learn, and reorganize (Marshall and Smajgl 2013). For these reasons, context-specific interventions and science-management partnerships are needed to enhance adaptive capacity among diverse managers, rather than assuming that a single homogenous approach will effectively accommodate all managers (Marshall and Smajgl 2013; Joyce et al. 2013).

4.1 Adaptation strategies for livestock production systems

Adaptation in grazing and confined livestock systems will require enhanced decision-making that integrates biophysical, social, and economic considerations (Nardone et al. 2010). Table 1 summarizes an assortment of adaptation strategies, which vary greatly in the extent of modification required, timing of implementation, specificity of impact, potential for success or failure, and likelihood of adoption given managers' diverse adaptive capacity (Briske et al. 2015). Many of the potential adaptations identified in Table 1 are already practiced (to varying degrees) in the NGP, providing natural opportunities for peer-to-peer learning and incremental improvements of existing adaptation strategies. Adaptations that could be further explored include using livestock as ecosystem engineers (Derner et al. 2009), shifting the composition of livestock breeds or species (Peinetti et al. 2011), developing robust drought contingency plans (Kachergis et al. 2014), and building flexibility into herd management plans (Torell et al. 2010; Derner and Augustine 2016).

Adaptive capacity within the agricultural community can be strengthened though the development of social learning networks that included learning from peers and collaboration with science-based organizations. It is critical that development of adaptive capacity focus on context-specific decision-making at the enterprise level (Roche et al. 2015). Adaptive grazing

Table 1 Typology of incremental adaptation, and systems adaptation and transformational adaptation strategies (Rickards and Howden 2012) for grazing and confined livestock operations in the Northern Great Plains

Incremental adaptation strategies	Systems adaptation and transformational adaptation strategies
Grazing livestock	
Adaptive grazing management	Livestock as ecosystem engineers
Altered timing of grazing and longer grazing seasons	Robust contingency drought/deluge planning
Proactive flexible stocking	Collaborative adaptive management
Nitrogen supplements to offset low forage quality	Shift in livestock breeds/species
Inter-seeding with nitrogen-fixing legumes	Geographic relocation of production enterprises
Targeted grazing of invasive plants and riparian vegetation	Shift to new production enterprises emphasizing alternative ecosystem services
Monitoring management outcomes to support subsequent decision-making	Breeds locally adapted to hot and fluctuating weather regimes
Monitoring and suppression of invasive plants in areas of likely invasion	Strategic, cost-effective nitrogen supplementation informed by diet quality monitoring, and associated decision-support tools
Cattle breeds genetically predisposed to graze on uplands or slopes of rugged terrain	Social learning networks
Modification of livestock enterprise structure	
Confined Livestock	
Altered pen direction, orientation, and slope	Altered designs of containment facilities for manure and runoff resulting from increased frequency of extreme precipitation events
Increased insulation in facilities	Genetic changes for greater heat stress tolerance (species, color, hair coat thickness, etc.)
Tunnel ventilation	Geographical shift in primary areas of confined livestock facilities
Stir fans	
Shade	
Sprinkler cooling	
High-pressure misting	
Evaporative cooling pads	

management is capable of exploring important complexities in a system, such as how to match animal demand with forage production variability across years and within the grazing season. In drought-prone rangelands, adaptive grazing management relies heavily on enterprise and management flexibility, specifically (1) matching forage availability with demand through flexibility in the proportion of cow-calf pairs versus yearlings and (2) using relevant monitoring metrics to inform flexible decisions that can reduce risk (Derner and Augustine 2016). Flexibility of enterprises and management also positions producers to make better use of weather and climate forecasts which can further reduce vulnerability to drought.

In regions of highly variable forage production, maintaining grazing flexibility by shifting from cow-calf enterprises to mixed cow-calf and yearling cattle (stocker) enterprise may be critical for economic success. This shift in strategy would allow producers to sustain desired cow herd genetics by maintaining a stable, albeit smaller, number of breeding cows more consistently by eliminating the need to liquidate cows during drought and restock following

the end of drought. However, this form of flexibility imposes additional costs and financial risks that may be unattractive to some managers (Torell et al. 2010). Limited adoption of flexible stocking strategies may also be due to uncertainty of seasonal precipitation forecasts (Derner et al. 2012), and inherent constraints in enterprise structure, such as maintaining desired herd genetics. Regarding enterprise structure, increased climatic variability may require greater use of stored forage (e.g., grass banks, hay supplies), increased contingency planning, and the ability to alter herd sizes and production systems, all of which require capital investment (Didier and Brunson 2004). Policies designed in a way that avoid perverse incentives, which could unintentionally increase vulnerability (Lark et al. 2015), could provide financial incentives to increase adoption of various risk-management strategies, including contingency planning and risk-management tools like insurance, if designed to avoid moral hazard (Muller et al. 2011). Decision tools could help producers explore trade-offs between profitability and financial risk of various adaptation strategies, perhaps increasing their willingness to experiment with them (e.g., Ritten et al. 2010; Moss et al. 2014).

In cases where incremental adaptation proves insufficient to sustain agricultural livelihoods, systems adaptation and transformational adaptation may be necessary (Rickards and Howden 2012). Systems adaptation and transformational adaptation involve making major changes in the production system that emphasizes the provision of alternative ecosystem services that are more consistent with the emerging climatic conditions (Kates et al. 2012; Joyce et al. 2013). For example, transformational adaptation in the NGP, in response to warmer and wetter conditions, may involve conversion of from extensive to more intensive agricultural systems that may result in substantial trade-offs among ecosystem services in the region. Consequently, adaptation strategies should be designed to accommodate both agricultural production and conservation goals such as geographical relocation of a producer's enterprise to climatic conditions more conducive to their success (Kates et al. 2012; Joyce et al. 2013).

4.2 Adaptation strategies for confined livestock

Projected warming will increase the potential for heat stress for both grazing and confined livestock, but the concern is greater for confined animals. For outdoor-confined operations, temperatures can exceed 55 °C in an unshaded feedlot on hot, sunny days (Brown-Brandl et al. 2010). An outdoor-confined animal's microclimate is defined by pen location, slope, and surface maintenance. Slope affects the angle of incident solar radiation and the heat load that animals receive. In the northern hemisphere, south, southwest, and west-facing pens receive the most intense solar radiation (Busby and Loy 1996). Regarding surface maintenance, manure has greater water-holding capacity than soil (Khaleel et al. 1981), so a wet manure-soil mixture will prevent water from draining out of pens after rainfall events. This standing water then increases humidity in the animal's local environment, making hot days feel hotter and cool days feel cooler. Containment facilities for managing animal waste and runoff will need to be adapted to account for projected increases in the frequency of extreme rainfall events.

Adaptation strategies to reduce heat stress and increase well-being for outdoor-confined animals include shade structures, sprinkler cooling, high-pressure misting, or evaporative cooling pads. Similarly, heat stress of indoor-confined animals can be reduced by increasing their housing facility's insulation, and installing stir fans, tunnel ventilation, or an evaporative cooling system. Stir fans and tunnel ventilation increase air velocity over animals to increase

convective heat loss, whereas evaporative cooling directly cools the air around the animals. It is known that windbreaks can be detrimental on hot days by reducing convective animal cooling (Mader et al. 1997), though they are beneficial to animals on cold days by reducing wind-chill effects (Mader 2003). Spanning all three types of livestock production systems (rangeland, outdoor-confined, indoor-confined), one final adaptation strategy for a warming climate is selecting heat-tolerant breeds or specialized genotypes such as Brahman, Criollo, Santa Gertrudis, Senepol, Tuli, and associated crosses (Gaughan et al. 2010; Hammond et al. 1998; Peinetti et al. 2011). Little is known, however, about genetically based tolerance to extreme temperature fluctuations, and concerns exist regarding the marketability of these alternative breeds or specialized genotypes.

5 Conclusion

Projections of increasing atmospheric CO_2 concentrations, warmer temperatures, and more intense rainfall events for mid- and late-twenty-first century offer unique challenges and opportunities for livestock production in the NGP. Livestock managers in the NGP may benefit from increases in forage production and shorter, milder winters—provided they can appropriately supplement livestock to mitigate declining forage quality, and are prepared to absorb and adapt to extreme weather events (e.g., deluges, heat waves, and winter storms). Adaptations in both grazing and confined livestock systems will require enhanced decision-making skills capable of integrating biophysical, social, and economic considerations, as socio-economic reasons are often prominent in producers' decisions regarding adoption of adaptation strategies (Marshall 2010; Nardone et al. 2010). In turn, this will require development of greater adaptive capacity for livestock producers to contend with the opportunities and challenges associated with regional climate change. The establishment of social learning networks, including peer-to-peer learning, where lessons from early adopters can be used to improve existing adaptation strategies and encourage others to experiment with them, will be essential for development of effective adaptation strategies (Didier and Brunson 2004). In fact, many adaptations have already been implemented, to varying degrees, in the NGP, providing opportunities for assessment, further development, and increased adoption. For adaptations that have not yet been implemented, decision tools can empower producers to explore the associated cost-benefit ratios, risks, and trade-offs among ecosystem services. Locally relevant climate data and weather forecasts can also be incorporated into these decision tools, to increase producers' adoption of new information to support management decision-making. The effectiveness of adaptation strategies to content with climate change will require context-specific decision-making skills that recognize both production and conservation goals.

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