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Review

Climate Change, Rangelands, and Sustainability of Ranching in the Western United States

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Abstract: Accelerated climate change is a global challenge that is increasingly putting pressure on the sustainability of livestock production systems that heavily depend on rangeland ecosystems. Rangeland management practices have low potential to sequester greenhouse gases. However, mismanagement of rangelands and their conversion into ex-urban, urban, and industrial landscapes can significantly exacerbate the climate change process. Under conditions of more droughts, heat waves, and other extreme weather events, management of risks (climate, biological, financial, political) will probably be more important to the sustainability of ranching than capability to expand output of livestock products in response to rising demand due to population growth. Replacing traditional domestic livestock with a combination of highly adapted livestock and game animals valued for both hunting and meat may be the best strategy on many arid rangelands. Eventually, traditional ranching could become financially unsound across large areas if climate change is not adequately addressed. Rangeland policy, management, and research will need to be heavily focused on the climate change problem.

Keywords: global change; GHG emissions; livestock and ranching production systems; drought risks; adaptation; mitigation; heat waves; energy

1. Introduction

The climatic volatility currently in progress involving global warming and increased extreme weather events will undoubtedly have major impacts on world rangelands and rangeland users over the next decade and beyond [1,2]. Rangelands as referred to herein can be defined as uncultivated lands that provide multiple ecosystem services for society, sustain habitat for grazing and browsing animals, and support the livelihoods of pastoralists and ranchers [3,4]. Under this definition rangelands comprise up to 70% of the world's land area and include natural grasslands, deserts, temperate forests, and tropical forests [3]. Greenhouse gases (GHGs) released into the lower atmosphere mainly by the burning of fossil fuels and other anthropogenic activities have caused the earth's temperature to rise by 1 °C since the 1860s [5,6]. If GHG emissions continue to rise, an increase in global temperature up to 3 to 5 °C is projected by the end of this century [6]. Extreme weather events are already increasing in frequency and severity in the US and globally [5–7]. Global concern is growing over the possibility that eventual irreversible, catastrophic climate change will result in massive loss of human livelihoods and mortality through adverse impacts on food production systems over both croplands and rangelands [5,6,8–14]. Rangelands globally account for 80–85% of feed needs for domestic livestock [3,15]. Hence, the impacts of climate change on the sustainability of rangeland livestock production systems will be globally significant.

Although climate change is now widely recognized as the biggest global threat to the future of humanity, it is an extremely difficult problem to solve. While there is global agreement on the immediate need to significantly reduce GHG emissions, climate change is a "tragedy of the commons" issue (see [16]) at the highest level in which no single country benefits from its own actions to limit GHG emissions as long as other countries are unrestricted in their emissions through enforced international agreements. This is also applicable to the need to address the sustainability of rangeland production systems collectively due to their large spatial extent. Local scale applications of mitigation and sustainability strategies may have limited effects as climate change impacts such as increased drought frequency and heat waves are mostly driven by global scale environmental changes linked to high GHG emitting developed countries. Social equity between affluent, developed, and poor, undeveloped countries is a critical and complicated consideration in formulating fair global scale climate mitigation and adaptation solutions. Contentious parts of any international agreement will involve how quickly large, highly developed countries (major GHG emitters) such as the US are required to reduce their GHG emissions and how much flexibility smaller, developing countries (minor GHG emitters) will have for emissions increases needed to improve living standards. In most cases, people in poor, undeveloped countries depend on rangelands and/or mixed (i.e., farm and ranch) livestock production systems as a major source of food supply.

There are potentially three key factors that can help in stabilizing the world's climate that include the following: (1) developing the capability to switch from non-renewable fossil fuels (e.g., coal, crude oil, natural gas) to renewable energy sources (e.g., wind, solar, biomass, hydro, geothermal, and tidal); (2) halting (or significantly reducing) the emission of GHGs from anthropogenic activities; and (3) stabilizing or reducing atmospheric GHG levels through various practices involving management of the land, ocean, and atmosphere [5,6,8,17–19]. How the world's rangelands are managed will be critical to the fate of the planet's climate and humanity. This is because rangelands, which account for 50 to 70% of the world's land area, depending on their definition, are primary providers of ecosystem services and processes (e.g., carbon sequestration, hydrologic cycling, nutrient cycling, air purification, biodiversity, and cultural services), including climate stability, which are essential to human life [3,15,20]. Further, rangelands are important providers of food, various other products, and cultural services.

Rangelands can and do play a significant role in climate change processes through a combination of factors that involve grazing ruminant GHG emissions, grazing ruminant management, shifts in landscape vegetation, sites for economic developments (subdivisions), sites for energy developments, and sites for carbon sequestration. Understanding how these factors (i.e., grazing ruminants, vegetation change, land use change) impact climate and rangelands is key in developing sound rangeland and ranch management strategies to mitigate and adapt to climate change. The main objective of this paper is to provide a current review of the linkages between rangelands, ranching, and climate change. While the analysis is generally focused on US rangelands, it also provides a relevant global perspective and suggests potential strategies for sustainable rangeland livestock production systems elsewhere.

2. Rangelands, Energy, and Climate Change

The area of world rangeland ecosystems (Figure 1) is being impacted by several opposing anthropogenic and natural processes that can result in (a) an increase in rangeland areas such as conversions of tropical forests into grazing lands, glaciated areas into rangeland, and cropland to rangeland due to climate change, soil degradation, and/or depletion of irrigation water supply from aquifers and drying of rivers [15]; or conversely (b) a decrease in rangeland areas such as conversion of arable rangelands into croplands, and rangelands into urban landscapes (e.g., [14]). For example, recent findings suggest that the depletion of large aquifers used for irrigation, such as the Ogallala in the Southern Great Plains of the US, is already causing shifts from cropland to rangeland [21]. Despite these findings, it is evident that there is a lack of information on the quantitative changes in rangeland spatial extent and quality (i.e., productivity) and their accuracy for different countries worldwide. This knowledge gap limits the ability to sustainably manage these ecosystems. Because rangelands are often viewed as unproductive marginal lands, public investment in research and development of rangeland-based systems is frequently low. This phenomenon is unlikely to change unless policy makers and society at large are made aware of the role that rangeland ecosystem services have in supporting human wellbeing [22]. Still, overall it appears that rangeland areas will experience a net increase in most parts of the world due to climate change impacts that involve desertification and retrenchment of snow and ice [15,21].

Conversion of rangelands to other land uses is frequently linked to human activities associated with energy and industrial development. Rangelands are often used for extraction of fossil fuels and renewable energy development. Since 2000, the impacts of energy development on western US rangelands have greatly increased due to rapid expansion of unconventional crude oil extraction and development of wind and solar power [23–26].

One study estimated that the losses of rangeland and forest landscapes from crude oil and natural gas development across central North America had increased 10 fold during the 2000–2012 period [25]. Estimates of rangeland losses to renewable energy development are lacking, but they will be substantial if wind and solar power become the primary replacements for fossil fuels [26,27]. Major adverse environmental impacts from energy developments on rangeland ecosystems include air and water contamination, loss of wildlife habitat, loss of livestock grazing capacity, increased earthquakes, and loss of esthetic values [24,26]. Conversely, energy developments are providing landowners with a significant source of income from crude oil and natural gas leases and provision of sites for wind and solar power developments [26]. How energy developments are impacting rangeland area and ecosystem services regionally and globally is an important knowledge gap that needs to be addressed in the future.

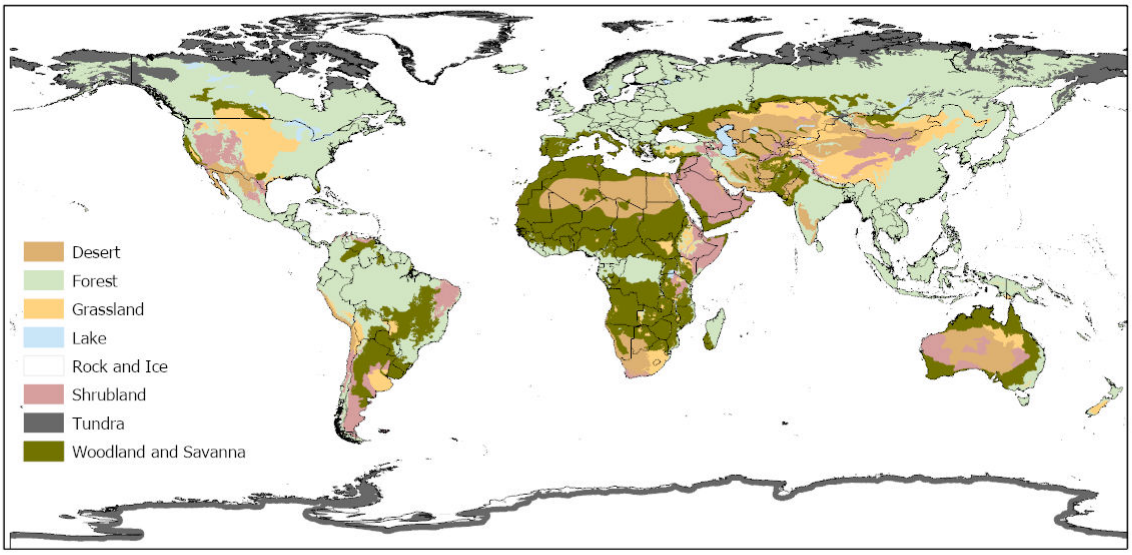

Figure 1. Distribution of global rangelands based on terrestrial ecoregions of the world (source: University of Idaho and World Wildlife Fund [28]).

Moreover, conversion of rangelands into economic/industrial developments such as buildings, roads, power lines, and pipelines can negatively impact their provision of ecosystem services and cause them to become significant contributors of fossil fuel GHG emissions Reducing the loss of farmland, forest, and rangeland landscapes from urban sprawl through more compact development can potentially reduce US fossil fuel use by 20% or more and thus significantly lower GHG emissions [29]. The US is slowly trending towards higher energy conservation (e.g., mass transit, multi-level apartments, inner city revitalization, toll roads) but still remains near the top of the list in terms of per capita energy use [29,30].

Some mitigation strategies have been introduced to slow conversion of rangelands into urban/industrial landscapes. Generally, these strategies are related to the adoption of land use regulatory policies and taxes (i.e., a top-down approach) as described in [26]. They include imposing taxes on fossil fuels, toll roads, restrictions on motorized vehicle use, and regulating land subdivision. These regulations can incentivize people to live in compact, high-density communities where various transportation needs can be met by walking or mass transit as opposed to long commutes by car. Through the application of these approaches, not only are fossil fuel emissions reduced, but other benefits include lowering fossil fuel depletion rates, reducing urban sprawl, minimizing habitat fragmentation, and reducing congestion and air pollution in cities. If aggressively applied, these approaches can potentially reduce global fossil fuel use (especially crude oil) by 20 to 30% within 10 to 15 years [26,29]. Energy conservation practices are widely applied in Europe, which has about one-half the per capita fossil fuel use of the US [26,30].

Financial incentives have also been advocated to protect rangelands from development and sustain or enhance their ecosystem services [20]. Commonly, landowners receive payments from non-government organizations for conservation easements, which are legal agreements to sustain ecosystem services and not develop specified lands [20]. Restoration practices can be a part of this approach. Land ownership in the western US is often an interspersed mosaic of private and public ownership [31]. Collaborative participation projects to minimize development and enhance ecosystem services over large rangeland areas of diverse ownership have evolved and increased since the early 1970s [31,32]. Examples of effective participatory conservation plans involving large, diverse western US rangeland areas were provided by [20,31]. Internationally, incentive programs similar to those used in the US have been effective in conserving African wildlife over large landscapes [33]. Taxes on fossil fuels were a commonly recommended means of funding financial incentives for tropical rain forest protection.

3. Contribution of Rangelands to GHG Emissions and Carbon Sequestration

3.1. Livestock and GHG Emissions

Globally, GHG emissions from livestock production (Figure 2) have received considerable attention in terms of both climate change causes and mitigation [2,34]. Various reports have provided estimates of total GHG emissions from world livestock production, but little information exists on how much livestock on rangelands contribute to the total. Assessments of livestock production's overall contribution to GHG emissions range from 10 to 51%. However, the Food and Agriculture Organization [35] estimate of 14.5% is the most commonly accepted number (Figure 2) [36]. Of this estimate, ruminants (cattle, sheep, goats) account for about 88% [36]. Depending on how rangelands are defined and whether landscapes converted from forest to pastureland are included, livestock on rangelands appear to account for 2 to 6% of GHG emissions.

Due to population growth, recent projections by [36] suggested that total world food production will need to be increased by about 50% by 2050. Demand for meat will go up by about 65%. In order to meet this demand for food by nearly 10 billion people (2.4 billion increase over the present 7.6 billion) without negatively impacting the environment, the World Research Institute (WRI) [36] has proposed a plan for sustainable food production focused mainly on increasing crop yields, reducing meat consumption by adapting to new human diets (with the focus on developed countries), reducing food waste, and reducing the demand for food through family planning assistance (i.e., managing population growth with the focus on developing countries). Under the WRI plan, sound rangeland management in combination with animal husbandry practices should reduce GHG emissions from ruminant meat production on rangelands, although the extent of this reduction is uncertain [2,36,38].

These key components are in-line with the United Nations (UN) Sustainable Development Goals for 2030 as specifically highlighted in a sustainability of livestock production sector report [39].

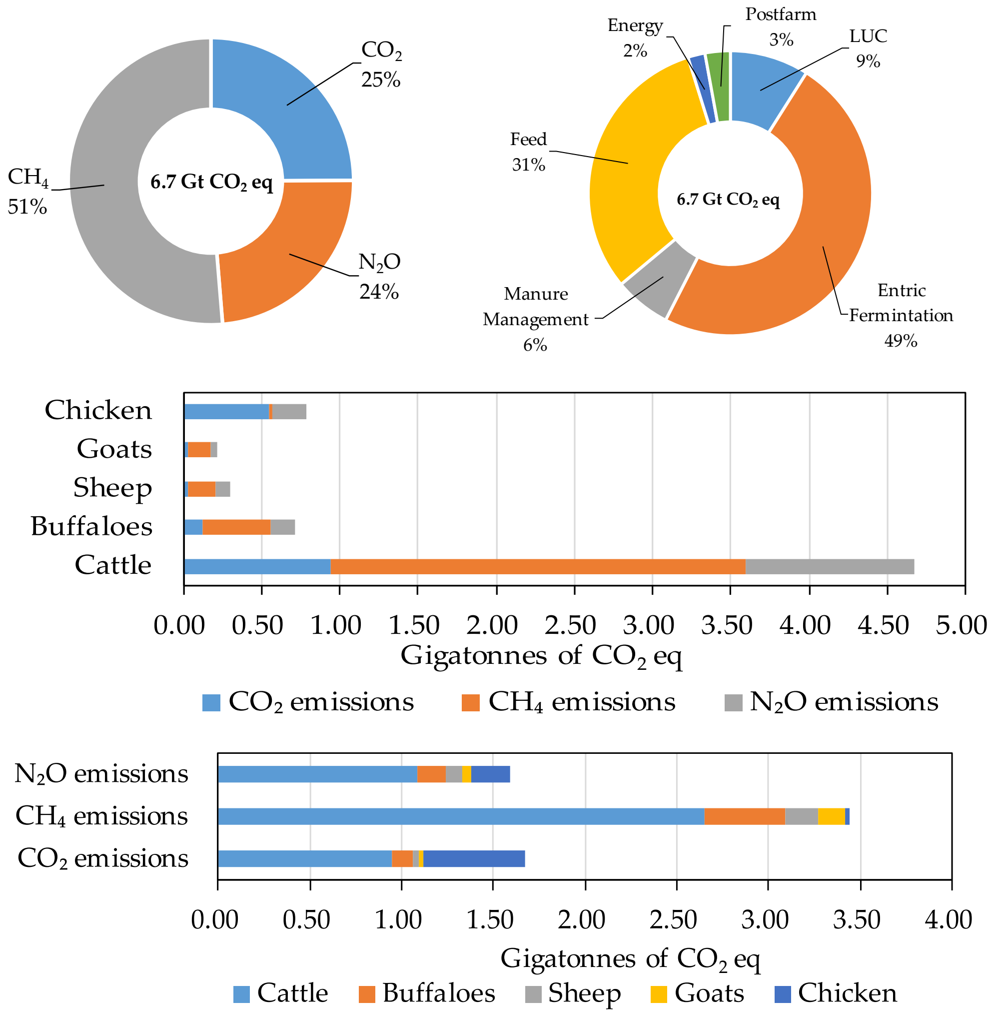

Figure 2. An overview of global GHG emissions from livestock supply chain by (1) the most emitted gases that include CH_4, N_2O, and CO_2 (top left panel); (2) production activities that include energy consumption, enteric fermentation, post-farm, land-use-change (LUC), and manure management (top right panel); (3) by animal species (cattle, buffaloes, sheep, goats, and chicken) (third panel); and (4) animal species per the most emitted gases (bottom panel). The data was based on FAO—Global Livestock Environmental Assessment Model (GLEAM)—Global greenhouse gas emissions from livestock summary of 2017 [35,37].

3.2. Rangeland Management and Carbon Sequestration

Livestock production systems can influence carbon sequestration on rangelands by affecting plant photosynthesis through tissue removal by grazing and incorporating plant material into the soil with their hooves. Excessive (over 50%) photosynthetic tissue removal generally impairs photosynthesis while partial (40% or less) tissue removal can enhance photosynthesis depending on various factors that include the plant species, soil moisture, temperature, and growing season (e.g., [3]). Standing dead material and rates of litter decomposition and its incorporation into the soil are impacted by grazing animal hoof action [40]. Very importantly, pasture management regimes based on manipulation of grazing intensity, timing, and frequency can influence the biomass and diversity of soil microbes, which control carbon turnover [41].

Overall, research findings have shown effects of livestock grazing on carbon sequestration have been inconsistent. A review of 67 studies from various global research sites that compared soil organic carbon (SOC) in grazed rangeland with that in adjacent exclosures found that SOC either increased, did not change, or decreased under grazing [42]. Livestock grazing on the driest and wettest rangelands (i.e., those below 400 mm or above 850 mm, respectively) was more likely to boost SOC by promoting increased root biomass production [42]. However, 15 studies conducted in the intermediate rainfall area (i.e., sites with ~400 to 850 mm of annual rainfall) reported that livestock grazing promoted either no change or a decrease in SOC storage [42]. This meta-analysis highlights the complexity of several interacting factors that can determine organic carbon storage in rangeland soils.

Stocking intensity appears to be the primary grazing factor affecting GHG sequestration on most rangelands, although information is limited. Research in Europe and the Northern Great Plains of the US has shown decreasing GHG sink capacity under increasing stocking densities [38,43]. Moderate stocking had higher GHG mitigation benefits than heavy stocking on Northern Great Plains native rangeland [38]. However, grazing exclusion appears to have no carbon sequestration benefit over moderate grazing. An intensive study in the shortgrass prairie of northeastern Colorado found no difference between 74-year-old exclosures and paired moderately grazed sites in SOC sequestration and total soil carbon [44].

Rotational grazing, especially the version commonly referred to as holistic planned grazing or non-selective regenerative grazing (also called mob grazing, cell grazing, managed intensive rotational grazing, short duration grazing, time controlled grazing, rapid rotation grazing, Savory grazing), has attracted much interest as a climate mitigation solution. Allan Savory's 2013 TED talk, "How to green the world's deserts and reverse climate change" [45], greatly increased the focus on this issue. However, the authors in [46] refuted Savory's claim that if scaled up, rangelands managed with his planned rotational grazing system could store enough fossil fuel carbon in the atmosphere to reverse climate change.

Some producers have reported successful use of a planned holistic grazing approach with regard to both profitability and environmental improvement [47,48]. However, only about 5% of ranchers appear to actually use a holistic approach based on a survey involving 765 California and Wyoming ranches [49]. Quantitative information on how it compares with continuous or simple rotation (two to five pastures) grazing at equivalent stocking rates in terms of soil carbon sequestration is limited. In the tall grass prairie of north Texas [50] found that adaptive multi-paddock rotation grazing at a high stocking rate and grazing exclusion resulted in higher soil organic matter and cation exchange capacity than either light or heavy continuous grazing. In general, soil health and proportions of late seral grasses were higher under multi-paddock rotation than continuous grazing at light and heavy stocking rates. An important experimental criterion in this study was that the same management had been applied to all ranches for at least nine years. In a Midwestern US study, it was found that adaptive multi-paddock rotation grazing could sequester large amounts of soil carbon and completely offset grazing cattle carbon emissions [51]. However, in contrast, a recent whole-ranch case study that was conducted in southern Patagonia showed no advantages of holistic planned grazing over moderate continuous grazing in terms of plant diversity, vegetation patches (size and number), bare soil, soil stability, rainfall infiltration, or nutrient cycling [52]. Although this study did not assess SOC directly, the Land Function Index they used (a common monitoring tool in holistic planning) suggested lower nutrient recycling rates (and presumably less SOC sequestration) in holistic planned compared to moderately grazed pastures [50].

On most rangeland landscapes it appears that two to four pasture rotation systems in combination with conservative to moderate stocking rates will optimize various controlled grazing benefits in terms of vegetation, soils, livestock productivity, wildlife, riparian health, and ranching profitability [3,49,53,54]. However, research focusing on how different controlled grazing approaches affect SOC is limited and inconclusive. Because rangeland livestock production operations are generally well managed in the US in terms of stocking rate, nutrition, and husbandry, the potential for CO_2 and CH_4 emissions reduction appears to be relatively low [2,38].

3.3. Would Intensified Rangeland Management Help in Mitigating Climate Change?

A number of studies suggested that intensified rangeland management is unlikely to be a major contributor to climate change mitigation (e.g., [2]). The findings by [2] were based partially on an assessment by [55] that indicated forestry and agricultural soil management might achieve ~15% of an overall strategy to stabilize the climate over the next 50 years. More recently, [56] found a combination of 20 land management practices applied across forests, wetlands, farmlands, and rangelands could provide over a third of the cost effective climate mitigation needed between now and 2030 to keep the global temperature increases below 2 °C. In this analysis, best case grazing management only accounted for ~1 to 2% of needed climate change mitigation, which supports the conclusion by [2]. Reforestation, avoided forest conversion, and natural forest management practices accounted for roughly 25% of total needed mitigation with farmland and wetland management practices accounting for another 4% and 3%, respectively [56].

If the full potential of rangelands to sequester CO_2 was realized in the US, about 2–4% of its emissions might be offset [2,57]. However, the long term storage dynamics of this CO_2 in the soil is uncertain, complicated, and depends on several factors discussed by [46,58,59]. In terms of methane emissions from extensive livestock production on rangelands in the US, authors in [2] estimated that improved grazing and livestock management might lower them by up to 20%.

The capacity of grazing lands to sequester CO_2 has probably been mis-estimated by most assessments due to underestimation of carbon storage in soils as indicated by [60]. Below ground biomass contains twice as much carbon as the atmosphere [61,62]. Grasslands sequester most of their carbon below ground in contrast to forests which primarily store carbon above ground in wood [60]. When grasslands burn, the carbon stored underground remains mostly unmodified but when forests burn large releases of carbon from wood occur in the atmosphere [60]. Carbon sequestered by grazing lands can persist in the soil for extremely long time periods [60]. A recent California, US study found grasslands can store more carbon than forests because they are less sensitive to droughts and wildfires [63]. A global data set of 836 paired sites analyzed by satellite imagery techniques showed land conversion from either cropland or forest into grassland leads to SOC accumulation [64]. After reviewing over 115 worldwide studies, authors in [65,66] concluded that grassland can act as a significant carbon sink with implementation of improved management practices (improved grazing management, sowing legumes, fertilization, and introduction of earthworms, among others).

4. Climate Change and Sustainability of Western US Ranching

This section highlights climate change adaptation strategies that can be used by rangeland livestock producers to enhance the sustainability of both rangeland ecosystems (Figure 3) and livestock production [2,15,57]. While a summary of recent reviews of this subject by [2,15,57] is pertinent, the focus of this conceptual analysis is to specifically suggest risk management strategies that are relevant to ranchers' decision-making and that provide means to mitigating climate change impacts [1,67]. This section highlights six issues affecting the sustainability of western US ranching that include grazing capacity and forage production; woody plant encroachment and forage production; how to cope with increasing variability in forage production; adaptive management of livestock; management of ranching risks; and management of drought.

4.1. Grazing Capacity and Forage Production

One of the most serious potential climate change impacts on ranching is reduced grazing carrying capacity [1,67] to levels under which traditional rangeland livestock production operations become no longer financially viable. Until recently, information has been lacking on how climate change has actually been impacting the grazing capacity of different rangeland types. In the southwestern US, a study from New Mexico that used statewide historical data collected annually from 1920 onward found rangeland livestock carrying capacity was 20% lower in the 1976–2017 period compared to 1920–1975 [68]. Shrub encroachment and climate change (more frequent heat waves) were the primary explanations for the decline in grazing capacity since the mid-1970s. Another study from the Chihuahuan Desert of New Mexico, US, found that rangeland grazing capacity declined by about 43% over a 52-year period (1967–2018) [69]. The combination of higher summer temperatures and the increased frequency of drought events was the primary explanation for this decline. Due to low shrub cover (under 10%) brush invasion was not considered to be a major factor in grazing capacity decline [69]. The findings from both [68,69] supported the projections of [1,70,71] that under climate change grazing capacity will decline on southwestern US rangelands due to altered temperature and precipitation regimes that can result in more heat waves (Figure 4) and droughts.

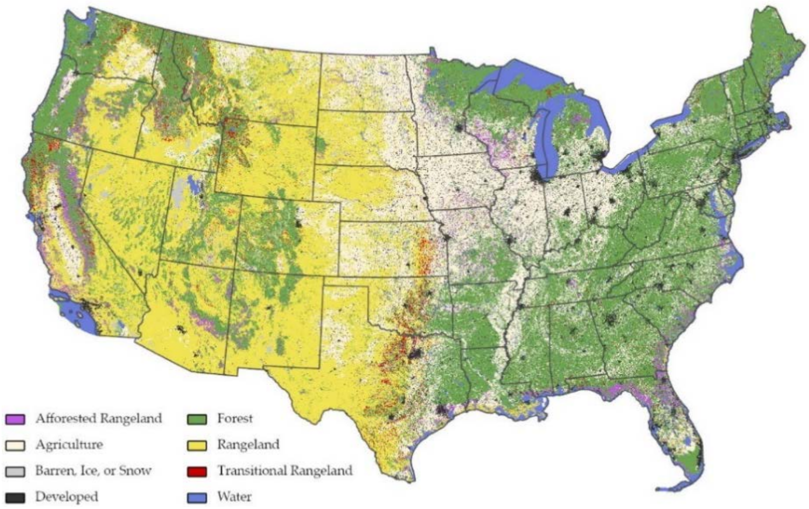

Figure 3. The extent and distribution of the conterminous US rangelands (source: [72,73]).

However, the opposite results to those of [69] in New Mexico, US (obtained under ambient rangeland conditions) were reported for a manipulative study in the Great Plains of Wyoming [74]. The study suggested that over a seven-year period, forage production increased in response to higher temperatures and CO_2 enrichment under controlled conditions [74]. Averaged across years, neither warming nor CO_2 enhancement had much effect on total forage production but in combination they increased forage production by about 38%. The effects of warming and CO_2 enhancement varied by year. During a drought year (2012), warming alone increased forage production, but added CO_2 had no effect.

Increasing precipitation variability is an expected climate change impact for nearly all world rangeland biomes [1,75]. In the Chihuahuan Desert, [69] found that the increased variability in precipitation during the last half of their 52-year study was a factor in lower rangeland forage yields along with more heat waves (Figure 4) and drought years. Drought years had a more negative impact on forage production than the positive effects of wet years. In a controlled field study in the Chihuahuan Desert of New Mexico grass productivity and total productivity declined but shrubs benefitted under conditions of increased precipitation variability [76]. This study also found that wet years did not compensate for dry years in terms of grass productivity.

In the central and northern Great Plains of North America, which have lower annual temperatures and higher precipitation than the Chihuahuan Desert, forage production may be increased (Figure 5) by climate change but at the expense of forage quality. On the shortgrass prairie in Colorado, US [81,82] and mixed-grass prairie in Wyoming, US [74], forage production was increased by elevated atmospheric CO_2 treatments, but forage quality in terms of crude protein content and digestibility was lowered. In a study in Wyoming, US [74], treatments of elevated warming and CO_2 in combination increased forage production by 38% but reduced forage N by 13% relative to current climate conditions. This reduced forage quality by lowering the protein content, increasing the fiber level, and reducing digestibility [74].

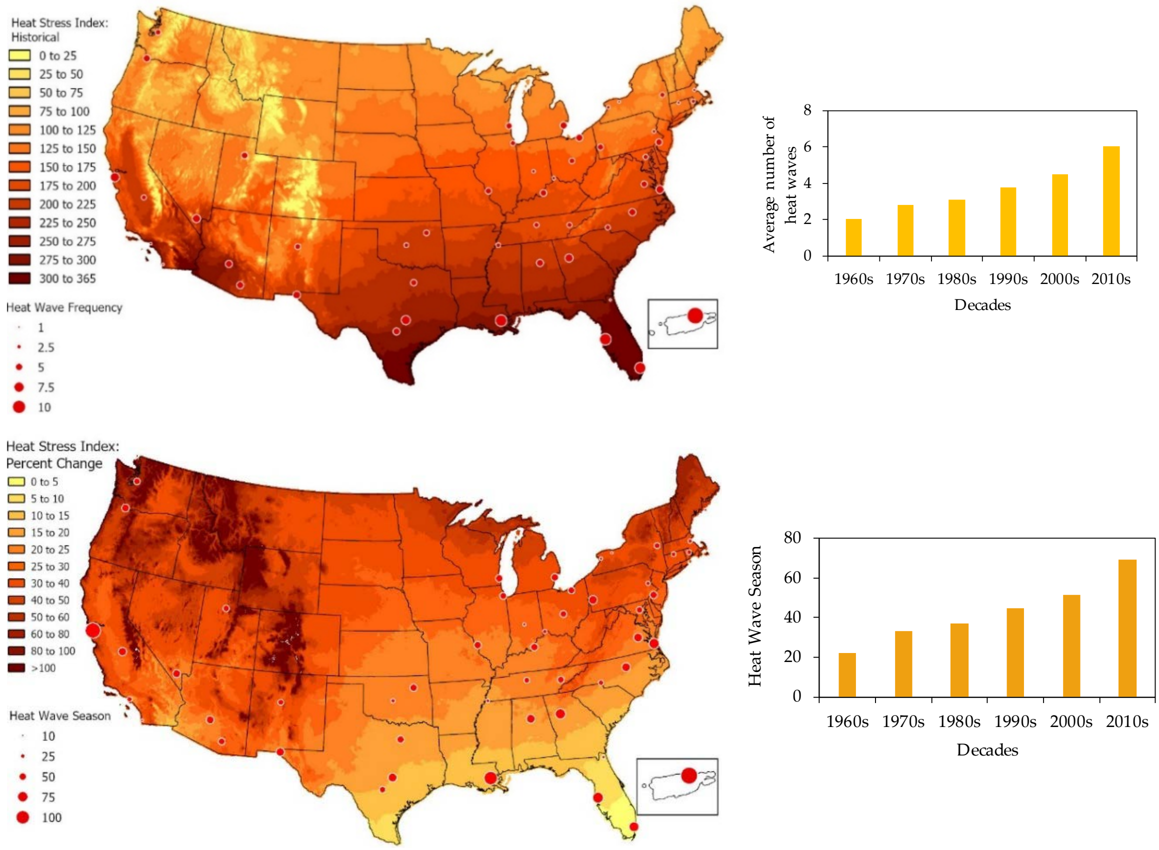

Figure 4. An overview of one of the climate change indicators, heat stress index (HSI), based on historical (1985–2005) (top left map) and future (2071–2090, climate change projection scenario RCP 8.5) (bottom left map) time periods showing the absolute number of days and percent change between the two periods. The HSI can be defined as the average number of days when the temperature–humidity index (THI) exceeds the recommended threshold for beef cattle (i.e., 74 °F) as indicated in [77]. The maps were overlaid with heat wave frequency and season length (days) based on analysis of air temperature over 50 cities in the US (both charts represent historical records 1961–2018) (sources: heat stress index maps US Forest Service [77,78], heat wave frequency and length US Global Change Research Program [79,80]).

Globally, vast areas of arid and semi-arid landscapes that now support livestock grazing are projected to become too hot and dry for economically viable ranching or pastoral operations. Worldwide, northern Africa, the Mediterranean Sea area, the middle east countries, India, and the southwestern US are projected to have the largest areas (mostly rangelands) that will become virtually uninhabitable. When average annual forage production drops below the 100 kg*ha^{-1} threshold, livestock grazing usually becomes financially unsound [83,84]. This is explained by excessive fixed costs per animal unit and low livestock productivity due to high energy expenditure in travel to meet nutritional needs [83,84]. Some rangelands in the Chihuahuan Desert may have already lost their viability for livestock production. On the Chihuahuan Desert Rangeland Research Center in southern New Mexico, US, 10 of the 19 years from 2000 through 2018 were below the 100 kg per ha forage production threshold compared to 8 for the 1969 to 1999 period [69]. Average forage yields for the 2000–2018 period was near 120 kg per ha, which is about one-third of the 90-year average.

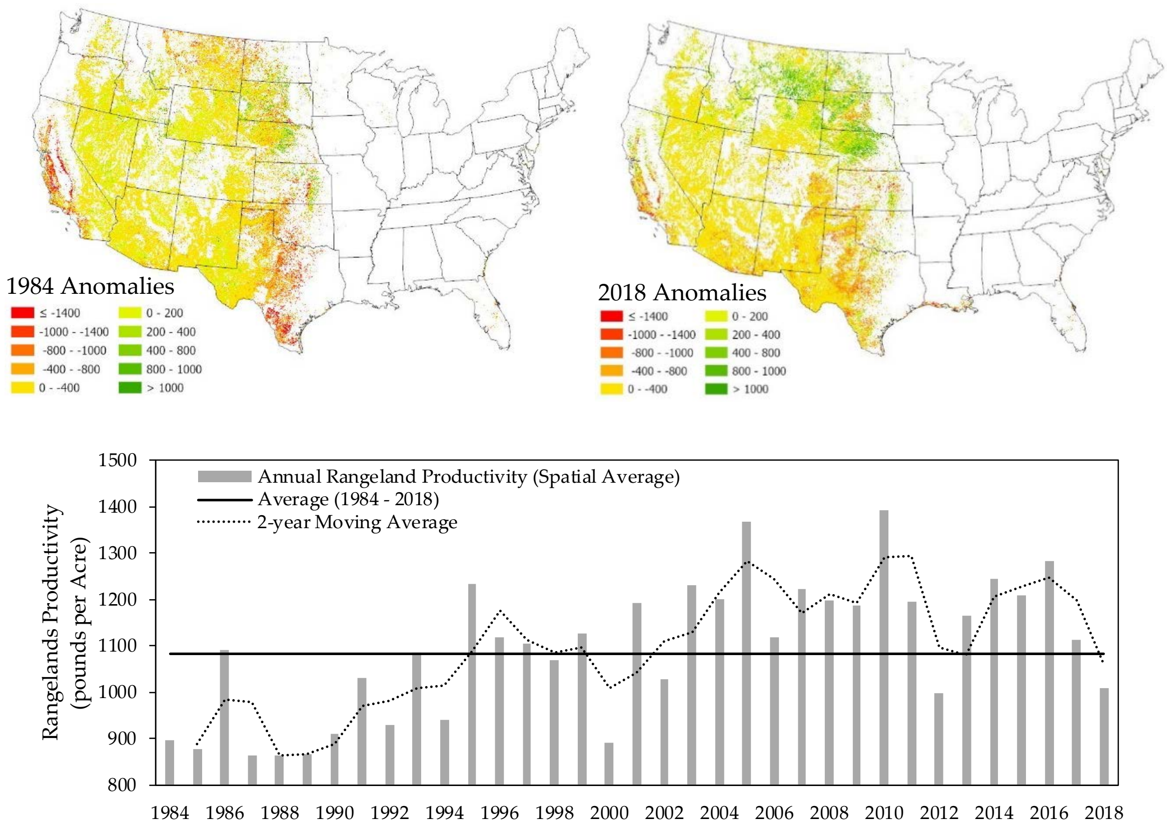

Figure 5. Rangeland productivity anomalies of the conterminous US for 1984 and 2018 (maps) and annual average productivity 1984–2018. The maps and chart are based on annual rangeland productivity maps developed as a function of normalized difference vegetation index (NDVI) at 30 m resolution (sources: [72,85,86]).

While forage yields will be decreased on many rangelands and may be increased on others (Figure 5) as the process of climate change plays out, forage quality will be adversely impacted, especially on more arid, nitrogen-limited rangelands [1,75]. Consequently, ranching profitability will be reduced because more supplemental feeding will be needed to sustain livestock productivity [70,74,75].

4.2. Woody Plant Encroachment and Forage Production

Encroachment of woody plants into grasslands and thickening of woody plant cover in savanna and forest areas has been an increasing global rangeland problem since the early 1900s [87–92]. Actual rates of woody plant encroachment have varied greatly by rangeland type and through time [89,90]. In general, woody plant invasion is accelerated by prolonged droughts and retarded by lengthy wet periods with some exceptions [3,89]. Annual increase rates in woody cover can vary from less than 0.1 to 2.5% depending on the vegetation type, soil, and climatic situation [90,92]. By some estimates, rangeland forage production can be reduced by 2% or more for every 1% increase in woody plant cover due to competition for moisture and nutrients, shading, and chemical inhibition. Excessive grazing by livestock and wildlife, altered fire regimes, seed dispersal by livestock and wildlife, extended drought, and elevated CO_2 levels are considered to be the primary drivers of woody plant invasion [90–93].

Rising levels of atmospheric CO_2 theoretically favor woody plants because most of them have the C3 photosynthetic pathway while native warm season range grasses have the C4 pathway [1,93]. Higher CO_2 levels can give a growth advantage to the C3 shrubs in a general sense with some exceptions [93]. Research supporting this hypothesis has been lacking, but it has recently been confirmed by a Colorado, US study on native rangeland [94]. Over a five-year period, aboveground biomass of a common shrub was increased several folds, whereas C4 grasses were little impacted on plots with artificially elevated CO_2 compared to controls. Based on this study it appears that the higher CO_2 levels driving climate change may have been an important factor favoring woody plant increases on many rangelands (e.g., [91]).

In general, SOC and total nitrogen tend to be increased by woody plant encroachment into grasslands, but there are exceptions and some complexities [2,90,91,95]. There can be tradeoffs among specific GHGs during the process of woody plant invasion such as increased carbon sequestration but also increased emissions of nitric oxide gas and non-methane hydrocarbons [95]. In a comprehensive review of various North American studies [90], it was found that woody plant encroachment in arid regions caused above ground net primary production to decrease relative to the historic vegetation. In contrast, increases occurred in semiarid and sub-humid regions. SOC response to woody plant encroachment across all studies had a net gain, although the range varied widely. Further, it did not appear to be closely linked to above ground net primary production. Taken collectively in the absence of disturbance, woody plant encroachment appeared to result in a net ecosystem carbon gain across species and regions. However, [90] emphasized another set of disturbances such as wildfire, land management practices, and drought may offset these gains and should be factored into regional scale C balance estimates.

4.3. Coping with Increasing Variability in Forage Production

Even on the more humid rangelands, livestock producers will likely have to cope with more erratic forage production (Figure 5) due to increased heat waves (Figure 4) and more variable precipitation. Although precipitation changes are not completely certain for various locations, climatic models are in agreement that temperatures will rise essentially everywhere causing the timing and amounts of precipitation to become more erratic [5,17,18]. While total precipitation may increase in the more humid areas, periods of wetness and dryness are likely to be accentuated, necessitating a shift to lower risk strategies. Developing a herd of well-adapted, experienced livestock will be of critical importance in avoiding high supplemental feed costs, disease and other health problems, and suppressed productivity from heat stress. Stocking strategies that minimize the need for partial or complete herd liquidation while optimizing profits will be critical as the climate change process advances. Research by [96] found light stocking of desert rangeland using a harvest coefficient of 25% reduced the need for destocking in drought years, facilitated range improvement, and gave quicker recovery from drought than conservative grazing (35–40% grazing use). Financial returns (cow–calf) were similar between light and conservative grazing. However, when the costs of periodic destocking and restocking were taken into account, light grazing was financially advantageous over conservative grazing. On semi-desert and desert rangelands, some researchers consider light grazing using a 25% harvest coefficient essential for drought survival [97]. Various other rangeland researchers have recommended a 25% harvest coefficient be used when forage is allocated to livestock in stocking rate decisions [98–101]. Few rangeland managers have the time, labor, or skills to quantify forage resources annually [100]. Because of a reluctance to destock, use of harvest coefficients above 25% has invariably lead to land degradation when drought occurs [15,97]. Reliable procedures for setting stocking rates were reviewed and demonstrated by [3].

Incorporating yearling cattle into cow–calf operations can be financially advantageous on arid and semi-arid rangelands. A New Mexico, US study found that adding flexible yearling stocking to cow–calf operations using conservative grazing increased average net ranch returns by 14% [102]. Optimal forage allocation between cow–calf and yearling enterprises was found to be 50–50. However, the authors commented that the increased expense and risk with this approach may not justify the returns for risk-averse ranchers. Flexible stocking could potentially double net returns relative to conservative stocking but realizing these financial gains depends on reliable climatic/forage forecasts that are not presently available [102].

4.4. Adaptive Management of Livestock

4.4.1. Genetically Adapted Breeds

As the process of climate change evolves, major changes in the types and breeds of animals grazed will be needed on many rangelands to adapt to rising temperature, heat waves, and limited drinking water supply. In arid lower latitude zones, a replacement progression of traditional cow–calf operations with yearling cattle [102], followed by sheep and goats, and lastly wild ungulates will likely be necessitated if climate change is not adequately controlled (Figure 6). In the upper latitudes, grazing with European cattle will become feasible across vast landscapes formerly suited only to wild ungulates because of cold. In lower and mid latitudes, the types of cattle grazed will shift towards those that can best handle harsh hot conditions, low quality forage, and limited water availability. European cattle breeds (*Bos taurus*) such as Hereford, Angus, and Shorthorn have advantages of faster growth rates and higher efficiency in the use of harvested feeds over Indian/African Brahman cattle (*Bos indicus*). However, Brahman compared to European cattle have more heat tolerance, disease tolerance, and capability to use lower quality feeds [2,103]. Ranchers in southwestern US now use mostly crossbred cattle that are roughly half Angus or Hereford and half Brahman. Raramuri Criollo cattle from northern Mexico, genetically adapted to hot deserts, are showing remarkable abilities to cope with the increasing nutritional and thermal stresses of the Chihuahuan Desert [104–106].

Some of the advantages of sheep and goats over cattle under climate change conditions, as reviewed by [2], include more tolerance of heat stress, lower water requirements, and capability to consume a broader array of forage types. Goats are especially well adapted to use hot desert areas dominated by shrubs. However, switching to sheep and goats requires more intensive management, and they are more vulnerable to predation than cattle. Over the last 30 years, higher labor costs and lack of qualified herders have been important factors in decisions by many ranchers in the southwestern US to switch to cattle and wildlife from cattle, sheep, and goats.

4.4.2. Game Ranching and Economic Sustainability of Ranching

Across the western US, fee hunting has become a major source of income on many privately owned ranches [3,107,108]. Compared to domestic livestock, native and adapted exotic game animals have advantages of requiring little input of labor or supplemental feed; they typically consume a wide range of forage species and have low water requirements, and several game species (especially African exotics) have high heat tolerance and are compatible with cattle at proper stocking rates [3,107]. Many ranches in the western US, especially Texas, derive more income from fee hunting than from livestock. However, common use grazing of domestic livestock and game animals is generally practiced because of complementarity.

The authors believe game ranching has a bright future in the US and several other parts of the world because of a growing demand for hunting leases, meat, and wildlife-oriented ecotourism [33,109–111]. On the other hand, the profitability of traditional rangeland livestock production operations may be adversely impacted by climate change [112,113]. The authors recognize that a major downturn in the US and global economy could alter the favorable situation for game ranching. Sport hunting and ecotourism have played a critical role in the conservation of wildlife on the rangelands of Eastern and Southern Africa [33]. Several species of non-native game animals such as gemsbok, Barbary sheep, and kudu from Africa, and axis deer and blackbuck antelope from Asia are now raised for trophy hunting on ranches mostly in Texas and to a lesser extent Florida [107,108,114]. Hunting for rare or threatened animals that are non-native is legally permitted in the US. Therefore, game ranching activities in the US boost their total numbers and provide a source of animals for restocking native habitats. A further benefit is that the US government requires that 10 percent of fees for hunting these animals be donated to conservation programs in their native habitats.

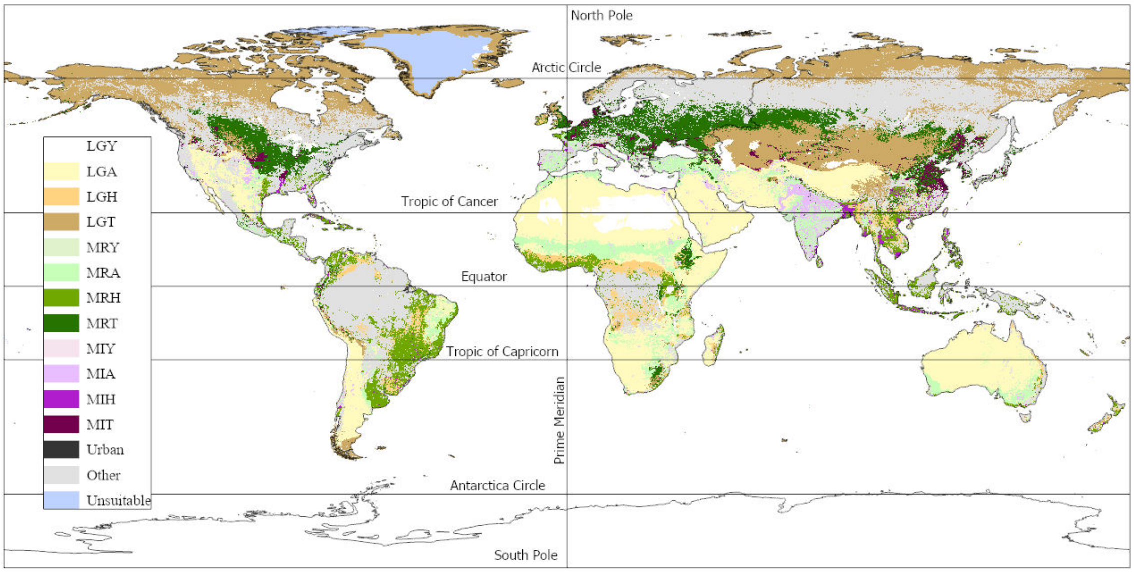

Figure 6. Global distribution of ruminant livestock production systems 2010 as developed by the FAO. Legend items represent LGY—livestock only systems hyper-arid, LGA—livestock only systems arid, LGH—livestock only systems humid, LGT—livestock only systems temperate (and tropical highlands), MRY—mixed rainfed hyper-arid, MRA—mixed rainfed arid, MRH—mixed rainfed humid, MRT—mixed rainfed temperate (and tropical highlands), MIY—mixed irrigated hyper-arid, MIA—mixed irrigated arid, MIH—mixed irrigated humid, MIT—mixed irrigated temperate (and tropical highlands), urban areas, other tree based systems, unsuitable (i.e., water bodies, snow and ice, and no data) (Sources: modified from [115–118]).

4.5. Managing Ranching Risks

Rangeland livestock producers in many areas will confront major challenges from climate change that will affect the sustainability of their operations over the coming decades. Fossil fuel depletion, freshwater scarcity, and increasing world debt are other challenges that will impact ranchers as well as the world economy and human living conditions. Big increases are expected in global meat prices, but simultaneously production costs and variability in annual forage resources will also increase [36]. The main risks that can affect the rangeland livestock production systems can be grouped into four categories that include climatic, biological, financial, and political as defined by [3]. It is projected that all these risks are likely to increase [2,15,57,103]. Management of these risks will probably be more important to the sustainability of most range livestock producers than increasing their capacity to expand livestock products to meet the increased demand [15].

Moreover, climate change-induced impacts can directly and indirectly drive political and financial risks. Ranchers and pastoralists in some arid and semi-arid equatorial and mid-latitude areas are now confronting increased heat waves and droughts (climatic risk) that make their operations less profitable and increasingly threaten their sustainability. In terms of financial risk, since the 1990s, there has been an increase in the frequency of cases in which ranchers (in the US as well as globally) must liquidate most or all of their herds under falling local prices and restock at high prices when the drought appears to be over [15,96,112]. When this occurs, ranchers confront the biological risks of disease infecting their livestock and low herd productivity due to placement of naïve livestock in an unfamiliar environment [15,96]. Political risks involving taxes, subsidies, land use regulations, price controls, and trade agreements will likely add more challenges. This is because governments will be under intense pressure to contain consumer prices (especially food), help repair damage caused by extreme weather events, reduce budget deficits, and reduce fossil fuel use both to mitigate climate change and slow their depletion [2,6,9,15].

Loss of water sources, increased wildfires, lower forage quality, increased noxious plant problems, accelerated woody plant invasion, and lowered livestock productivity from heat stress and disease are projected adverse impacts of climate change on rangeland livestock producers [1,2,57,103]. In the short term, rangeland livestock producers at mid and upper latitudes may derive some benefit from climate change in terms of less severe winters, longer periods of forage growth, and higher forage production due to CO_2 enrichment [70]. Opportunities for ranchers involve income potential from renewable energy developments, sport hunting, ecotourism, and provision of ecosystem services. Rangeland livestock producers who own their grazing lands are in much better position to derive benefits from climate change than those on public lands. On public lands, ranchers in the US are increasingly faced with loss of grazing privileges as more land is appropriated for renewable energy developments, and other lands are impacted by fossil fuel extraction [23–26].

Climatic instability, rising crude oil prices, fresh water scarcity, and extreme debt levels could interact to drive up global food prices and other living costs in the 2020s [15]. As market forces and government central banks respond to these factors, alternating periods of inflation and deflation will likely occur. Although livestock prices generally rose in the 1970s, short term downturns coupled to rising costs and interest rates were devastating to heavily leveraged livestock producers in the US [119]. In the southwestern US, ranchers who used a low input approach, minimized debt, and practiced conservative stocking were the most successful in surviving periods of drought and financial upheaval [96,119,120]. Various studies reviewed by [3,15] show this strategy has worked well on arid and semi-arid rangelands in other parts of the world as well.

4.6. Drought Management

Climate change will result in increased frequency and duration of drought, accentuating this ranching risk. Several effective drought management and mitigation strategies have been developed that involve integration of predictions of drought timing, severity, and length; management during and after drought; government drought relief programs; and socio-economic characteristics of the ranching operations in drought preparedness and response [112,121]. Basic drought decision and response theories were developed by [122] and summarized by [3] that involve characterization of ranch resources, defining the problem situation, assessment of knowledge (experience and information), identifying primary uncertainties, making key decisions (livestock numbers, supplemental feeding, leased land, cost adjustment), and planning drought recovery.

There are two important considerations involved in the interactive role of the government and the rancher in drought response, as discussed by [123]. These are that (1) pastoralists in countries with governments unlikely to intervene with financial aid are typically conservative and risk averse; and (2) feed subsidies during drought encourage non-sustainable stocking, undercutting the linkage between ecology and economics. The examples provided by [123] explain how modern financial and technological structures aimed at increasing flexibility and efficiency can delay making destocking decisions necessary to avoid catastrophic damage (e.g., rancher bankruptcy, irreversible rangeland degradation). The responsibility of the individual rancher to be aware of how much forage is available and to anticipate current and future demand through monitoring was emphasized by [123]. Key components of drought adaptation and mitigation strategies as discussed by [3,83,112,122–124] involve conservative use of forage, avoidance of over capitalization of the ranch, income diversification, and having both forage and monetary reserves.

Drought monitors, indicators, and forecasts in ranch decision-making are discussed by [112]. They suggest the use of various indicators such as the Palmer drought severity index (PDSI) and the vegetation drought response index (VDRI) for drought prediction. However, the lack of reliability for their site, the difficulty in accessing information, the difficulty in understanding the information, and cost were identified as possible reasons that a low proportion of ranchers were using drought monitoring and forecasting information. These reasons highlight the need for future research on existing barriers that may prevent ranchers from using available drought forecasting information [112] as well as the need to provide ranchers more refined climate risk management approaches. Readers are referred to [121] for a consideration of how socioecological factors of ranching operations affect their drought preparedness and coping strategies.

5. Key Sustainability Strategies

A summary of climate change-induced risks and impacts on rangeland livestock production systems as well as some of the traditional mitigation practices and means to enhance these practices to provide more adaptive sustainability strategies are shown in Table 1.

Table 1. Summary of climate change risks, impacts, mitigation, and sustainability strategies for ranching systems in the western US.

	Risks and Impacts	Traditional Mitigation Practices	Proposed Sustainable Strategies
Environmental	**Climatic**: Drought and heat waves, wildfires, Loss of rangelands to industrial and energy development, Loss of grazing capacity, Reduced ecosystem services, Loss of carbon sequestration potential	Traditional restoration practices *, Drought insurance and/or subsidies *, Destocking–restocking cycles, Livestock emergency feed inputs, Early weaning (cow–calf operations) *, Hauling water for livestock	Light grazing, Use of livestock to control fine fuels (wildfire suppression), Drought-adapted livestock breeds or species, Mixed livestock–wildlife enterprises, Use of sensors (both remote and on-the-ground) to aid in rapid decision-making, Increased geographic mobility (see below)
	Biological: Increased heat stress, Increased animal disease, Reduced animal productivity, Woody plant encroachment, Variable forage production and lower forage quality	Increased external feed inputs, Livestock genetics for high productivity, Increased veterinary inputs	Adapted livestock with higher heat and disease tolerance (even if less productive) and ability to include more browse (woody plants) in their diets, Use of livestock to control shrub encroachment, Use of sensors (both remote and on-the-ground) to aid in rapid decision-making
Socio-economic	**Financial**: Increased prices of critical inputs, Access to loans and cost of borrowing, Reduced financial profitability	Reduce debt and investment in capital improvements *, Conservative livestock grazing	Adapted livestock genetics, Niche markets, Ecotourism and sport hunting, Renewable energy developments on private land, Carbon credit markets
	Political: Reduced grazing privileges on public lands, Increased pressure to convert rangelands to other land uses	Regulations on land use and building, Conservation easements *, Government subsidies for rangeland restoration *	Public–private partnerships, Increase awareness of ecosystem services provided to society by working ranches (especially in areas prone to catastrophic wildfires)

(*) These practices could contribute to future sustainable strategies.

The authors agree with the point of view of [57] that "all adaptation is local and no single adaptation approach works in all settings". We hypothesize that across the western US, two general ranching adaptation strategies will prevail, either sustainable intensification or sustainable extensification, depending on the local net effects of climate change on an area's aridity (Figure 7). Sustainable intensification (SI) can be defined as a strategy that seeks to increase production per unit area on existing farmland (SI is usually associated with crops) in order to spare remaining wildlands and the ecosystem services they provide [125–127]. This strategy usually involves increasing external inputs on existing agricultural land as a means of maintaining or improving its productivity. Conversely, sustainable extensification seeks to maintain or increase farm income by producing agricultural commodities (i.e., crops or livestock) that require lower external inputs and that consequently exert a gentler footprint on the environment [128,129]. It is important to note our conceptual analysis did not use the term extensification as implying an increase in the conversion of forests or other wildlands to cropland as the findings by [130,131] do.

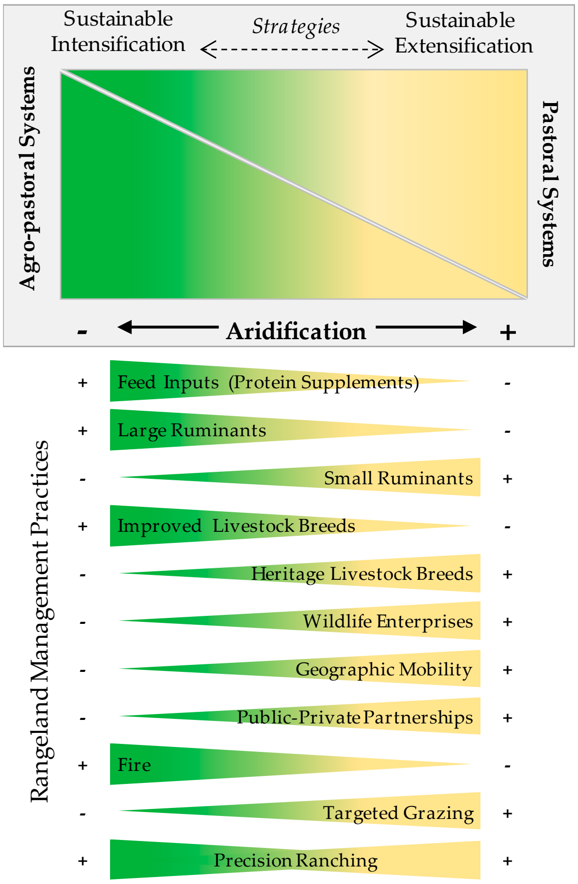

Figure 7. Conceptual diagram of adaptation strategies and rangeland management practices for ranching systems in the western US relative to predicted regional impacts of climate change. In regions predicted to become more arid, ranching systems are likely to evolve towards purely pastoral-like low-input systems and are predicted to remain viable using sustainable extensification strategies and tactics. At the opposite extreme of the continuum, in regions with little to no aridification, ranching systems are likely to evolve towards becoming agro-pastoral systems and are predicted to remain profitable using sustainable intensification strategies and practices.

In regions of the western US where aridification is expected to be negligible, such as the Northern Great Plains, the authors anticipate that to remain viable, ranching systems will likely need to evolve towards increased crop–rangeland integration (agro-pastoral systems). Conversely, in places predicted to become drier, such as the desert southwest, the authors anticipate that ranches will need to evolve towards becoming purely rangeland-based enterprises with minimal external inputs (true pastoral systems). On Northern Great Plains rangelands, there might be an increase in forage production (Figure 5) but a decline in forage quality [74]. Therefore, for financial viability and sustainable livelihood, ranchers in this area will likely rely on SI strategies [132] using a set of rangeland management practices such as improved animal genetics, increasing supplemental feed inputs, and increased use of controlled fire for habitat and forage quality improvement (Figure 7).

Conversely, declines in both forage quantity [69] and quality [75] will likely occur on the desert rangelands of the southwestern US. In order for ranching to be financially sustainable, implementation of sustainable extensification strategies using a different set of rangeland management practices such as raising low-input livestock adapted to hot and variable grazing conditions (whether heritage cattle breeds or small ruminants) and mixed enterprises (whether raising yearling cattle or mixed game/livestock operations) will be essential. In some instances, new public–private partnerships [133] will need to be developed to facilitate increased local-to-regional geographic livestock transfers to help reduce herd liquidation during droughts [134]. Because increased woody plant cover and decreased grassland productivity are expected to go hand in hand with aridification [76,135], the use of controlled fire to suppress shrub recruitment will be increasingly limited by the lack of fine fuels. If this scenario plays out, tools such as targeted grazing [136] might become a critical surrogate to the use of fire to control woody plant encroachment (Figure 7).

The authors anticipate that in the era of Big Data [137], the Internet of Things [138], and advanced data analytics [139], smart ranching decision support tools based on real-time data retrieval from sensors that are able to monitor weather, soils, animals, and infrastructure (e.g., water drinkers) will play equally important roles in allowing ranchers to adapt regardless of the direction of change in the system (Figure 7), hence increasing the resiliency of the rangeland livestock production systems.

6. Conclusions

Over the coming decades, rangeland livestock producers will benefit from a major increase in demand and prices for meat and other livestock products. The biggest challenge confronting ranchers and rangeland livestock producers will likely be climate change, which is expected to have region-specific impacts [70,75].

The use of conservative stocking rates across the board will likely continue to be an important tool to adapt to the increased variability in precipitation patterns and droughts. In all cases, this conceptual analysis suggested that strategies and management practices that improve the efficiency of ranching enterprises will play critically important roles. The importance of rangelands in terms of ecosystem services as well as food and fiber production will become increasingly significant over the next few decades as the forces of resource depletion and climate change intensify. Rangeland policy, management, and research will need to be heavily focused on the climate change problem. We recommend that research and extension funding involving ranch monitoring programs be strengthened at both federal and state levels. At the international level, multilateral organizations such as the UN must play an increasingly visible role in strengthening awareness among world leaders regarding the need to invest in rangelands and the peoples that depend on them. The biggest knowledge gaps at present involve the degree and rate of change that has recently occurred in climatic, land area, and forage conditions for different types of rangelands in the US and globally. Another major knowledge gap involves the proper assessment of how climate change is impacting the viability and profitability of rangeland livestock production operations in different rangeland regions and ecosystems. There is also a current lack of understanding on how climate change trends will influence livestock disease outbreaks. SI strategies (Figure 7) will likely alter the carbon and water footprints of rangeland-based beef production, but these relationships are still poorly understood.

Climate stability, water purification, air purification, nutrient cycling, and biodiversity are among the critical ecosystem services needed by human societies but often taken for granted by them. The global human population, now at almost 8 billion compared to one billion during most of human history, is jeopardizing the very foundation of ecosystem services on which it depends [9,10,15]. Based on the UN's projections, the world human population will likely exceed 10 billion by 2050 [36]. We strongly agree with [10] that endless exponential growth in human population and natural resource consumption is not compatible with human civilization sustainability.

Because rangelands account for 50 to 70% of the world's land area and generally support natural or near natural vegetation, they play a critical role in providing the ecosystem services essential for human existence [3,15,20]. Rangelands will undoubtedly become more important for ecosystem services, as well as food and fiber production, as the world moves towards 2050. This will occur as problems of global warming, scarcity of fresh water, species extinction, and contamination of air and water intensify in response to more people in the world desiring higher material and food consumption. Rangelands, when properly managed, can sustainably provide people with food, fiber, and ecosystem services [3,10]. Conversely, human societies must recognize that rangelands have a finite capability to provide these essential components of human life. At global, national, regional, and local levels, the authors consider the conservation and enhancement of rangeland landscapes a critical part of climate change mitigation and adaptation. Therefore, the authors advocate government policies and regulations that more heavily emphasize rangeland research and management as part of the solution to the climate change problem.

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