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The Impact of Climate Change on California Rangelands and Livestock Management

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Abstract: On a global scale, rangelands occupy approximately half of the world's land base surface; have a critical role in carbon sequestration and biodiversity; and support a diverse and critical economy, but at the same time, are under threat by many factors, including climate change. California rangelands, which are no exception to these aforementioned characteristics, are also unique socio-ecological systems that provide a broad range of ecosystem services and support a >$3 billion annual cattle ranching industry. However, climate change both directly and indirectly poses significant challenges to the future sustainability of California rangelands and, ultimately, the management of livestock, which has important economic implications for the state's agricultural economy. In this study, we examined the changes in overall climate exposure and climatic water deficit (CWD), which was used as a physiological plant water stress gauge, to evaluate potential impacts of climate change on various rangeland vegetation types across California. We used two downscaled global climate models, MIROC and CNRM, under the 'business-as-usual' emissions scenario of RCP8.5 at a mid-century time horizon of 2040–2069 and known vegetation–climate relationships. Using the models, we predicted climate change effects using metrics and spatial scales that have management relevance and that can support climate-informed decision making for livestock managers. We found that more than 80% of the area of the rangeland vegetation types considered in this study will have higher CWD by 2040–2069. We evaluated these results with beef cattle inventory data from the U.S. Department of Agriculture by county and found that, on average, 71.6% of rangelands in the top 30 counties were projected to be highly climate-stressed. We found that current proactive and reactive ranching practices such as resting pastures, reducing herd size, and rotational grazing may need to be expanded to include additional strategies for coping with declining plant productivity.

Keywords: rangelands; cattle; climate change impacts; climatic water deficit; adaptive ranching

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1. Introduction

Rangelands are among the most widespread and socio-ecologically significant plant-based land cover types on Earth. These critical systems are biodiversity hotspots, they represent important carbon sources, and they are economically critical for millions globally, including those in California. California rangelands are critical to the livestock sector of the agricultural economy, providing three-quarters of the forage [1]. These rangelands also provide essential ecosystem services, including wildlife habitat, watershed services, recreational opportunities, and open space [2]. Two of the six U.S. biodiversity hotspots include California rangelands [3,4]. Additionally, rangelands have a critical role in carbon sequestration, which may serve in mitigating the effects of climate change [5].

The rangelands in California generally consist of grasslands that are largely non-native and annual, with a smaller fraction of perennial grasses. But many other important vegetation types are also classified as California rangelands, including the state's deserts, oak-dominated woodlands, shrublands, hardwood, and other pine and fir woodlands or forests, covering half the state (~57 million ac) [6].

However, the effects of climate change are already affecting the state's rangeland ecosystems in predictable and, in some cases, unpredictable ways, and these climate-mediated events are expected to become more acute in the years and decades to come [7,8]. The average high and low temperatures are rising, as are extreme heat events and heat waves, and more frequent, severe, and long-lasting droughts have also been recorded [9,10]. In fact, two of the most severe droughts in the past 1200 years have occurred in just the last 15 years. These climatic conditions and dynamics will result in greater plant stress, promote changes in vegetation species composition and community assembly, and likely result in marked changes in forage type and, presumably, reductions in forage availability [10]. Climatic changes also increase invasive species pressure and disturbance events such as wildfires. Cheatgrass is an increasingly common annual grass in California rangelands and has benefited from warming due to climate change [11]. Other factors are more difficult to model and predict, including how a changing climate could facilitate increased pressure from new pests and other pathogens. Traditional ranching may become economically unsustainable if climate change is not addressed [12].

To anticipate and help prepare for the direct and indirect effects and impacts associated with a changing climate on California rangelands, we used climate exposure and climatic water deficit (CWD) projections as proxies for potential climate impacts and plant stress at spatial scales that are meaningful for rangeland management and operational decision making. These climate projections were considered at the county level in combination with beef inventory data and by the major rangeland vegetation type statewide. The results of this study can provide a science-based foundation and context for ranchers, technical assistance providers, and policymakers to better understand expected future conditions due to climate change on the state's rangelands, and to consider different or alternative management strategies for more sustainable and resilient ranching operations for this important agricultural industry.

2. Materials and Methods

In this study, two different global climate models (GCMs) were used in order to project the anticipated mid-century (2040–2069) climate conditions for California at the spatial resolution of the county. The two climate models that were used were CNRM CM5 and MICROC ESM. The CNRM CM5 model predicts moderately warmer, but slightly wetter future conditions compared to what the state has experienced historically. In contrast, the MIROC ESM predicts much warmer and drier future conditions expected with climate change. These models were chosen because they cover California's future climate forecasting range [13,14] across the continuum of expected future outcomes. Each of these climate models was run using the high, or RCP8.5, greenhouse emissions scenario. RCP8.5 is considered a 'business-as-usual' scenario and does not incorporate any specific climate mitigation targets, or any local, state, or even global policies or compacts; nor does it consider the potential mitigating role of technological advancements that would otherwise reduce the actual global emissions. While global, national, and subnational efforts are in place to curb greenhouse gas emissions [15], we opted to use the RCP8.5

scenario as it is more closely related to current emission trends than any lower emissions rate scenarios [16].

We used baseline (1980–2010) temperature and precipitation averages and the same GCM-projected variables as inputs for a hydrological model provided by the United States Geological Survey called the Basin Characterization Model (BCM) [17–19]. The BCM is a process-based model that balances the hydrological budget with climate and site conditions across large geographic areas. Such models are useful because they indicate how changes in primary climate variables (i.e., temperature and precipitation) interact with environmental conditions, including soil depth and porosity, topography, and bedrock, affecting the biological processes and ecological dynamics. We used the BCM to determine hydrologic values including CWD, which is being used as a surrogate for water stress by plants. We recognize that future expected changes in temperature and/or precipitation alone do not represent the full composite of characteristics for how rangelands will be shaped by future climate change, and are not attempting to simplify the inherent complexities of these systems. Factors associated with other environmental stressors and disturbances, both climate-mediated and otherwise like wildfires, extreme heat events, extreme flooding, or even high wind events and land-use patterns, will also shape and influence vegetation dynamics across California rangelands.

We defined seven types of rangelands, based on the Wildlife Habitat Relationship (WHR) vegetation types used by the California Department of Forestry and Fire Protection of the California Natural Resources Agency [20]: Conifer Woodland—Juniper and Pinyon-Juniper; Desert Shrub—Desert Scrub, Desert Succulent Shrub, Alkali Desert Scrub, and Desert Wash; Desert Woodland—Joshua Tree, Desert Riparian, and Palm Oasis; Hardwood Woodland—Blue Oak-Foothill Pine, Blue Oak Woodland, Eucalyptus Hardwood, Coastal Oak Woodland, Valley Oak Woodland, and Valley Foothill Riparian; Herbaceous—Annual Grassland and Perennial Grassland; Shrub—Mixed Chaparral, Chamise-Redshank Chaparral, Alpine-Dwarf Shrub, Bitterbrush, Low Sage, Coastal Scrub, Montane Chaparral, Sagebrush, and Undetermined Shrub; and Wetland—Marsh, Fresh Emergent Wetland, Saline Emergent Wetland, and Wet Meadow (Figure 1). All the analyses were conducted on all the land types classified by each rangeland type, as described above, and are completely independent of whether or not that land was being grazed at the time of the study or not.

Two different, but complementary, analyses were conducted and are presented in this study: (1) the difference in climatic water deficit (CWD) and (2) the climate exposure comparison between a baseline period of 1980–2010 and future projections in 2040–2069. In order to calculate the change, we split the California study areas into 270 m^2 grid cells according to the methodology of Flint et al. (2013) [18]. Historical temperature and precipitation data as BCM inputs were obtained from PRISM [21], which outputted 30-year averages at 270 m^2 grid resolution [18]. The BCM also created the downscaled GCM-projected future climate variables for the same 270 m^2 grid cells.

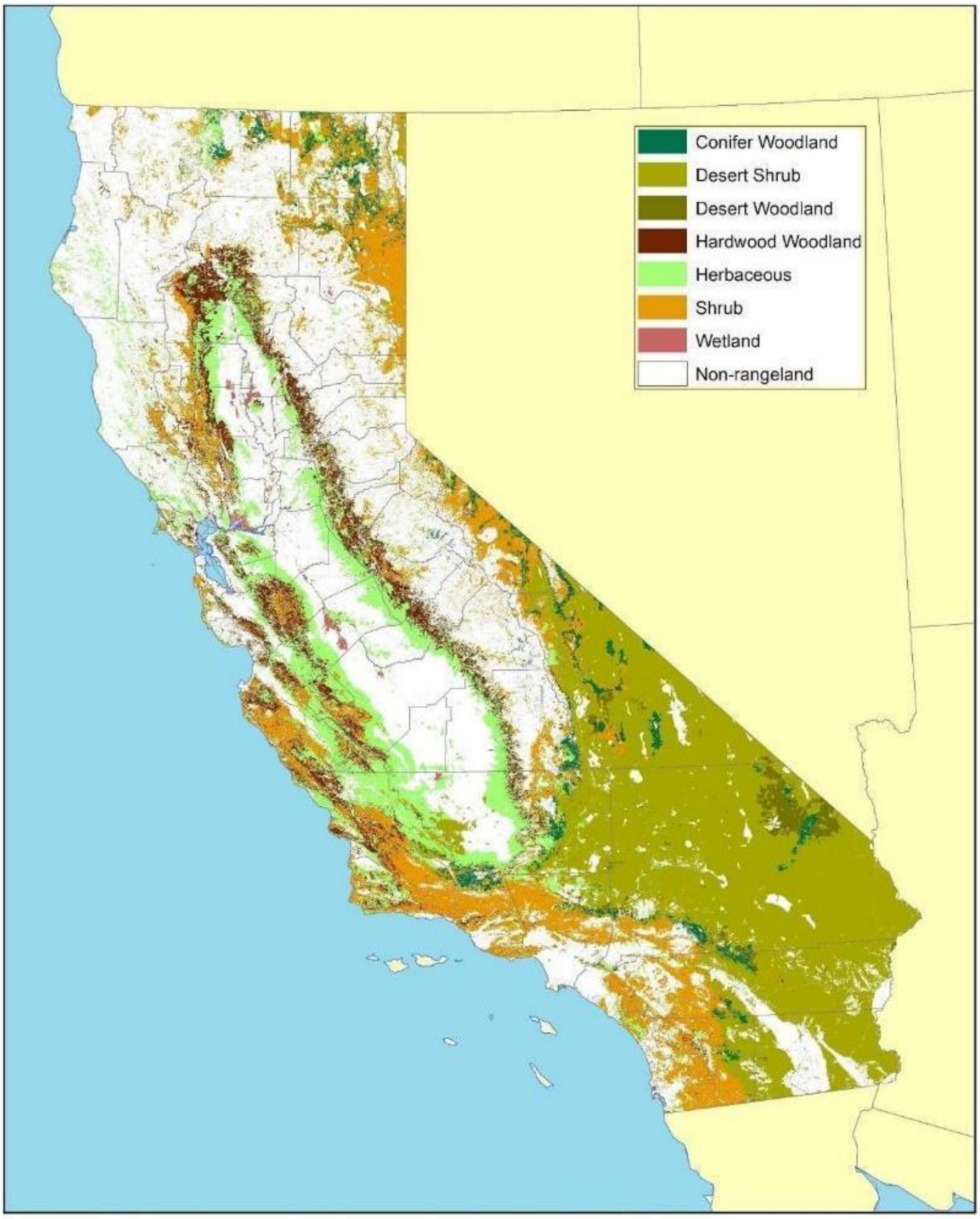

Figure 1. Illustrated are the general California rangeland vegetation types considered.

2.1. Determining Climate Exposure

Climate exposure is defined as the degree of difference between historic and projected future changes related to climatic attributes (temperature or precipitation) that a species, population, or community is anticipated to experience due the effects associated with future global climate change [10,22]. We modeled and projected the future climate exposure of rangelands in the state of California based on a set of important meteorological and hydrologic variables, including climatic water deficit (CWD), which is a useful and physiologically meaningful proxy for assessing plant water stress. Climatic water deficit (CWD) is an index of plant stress which is arrived at by subtracting actual evapotranspiration, which is limited by soil moisture availability, from plant evaporative potential [23]. This measure provides an estimate of the unmet plant water demand, which can be spatially portrayed through the BCM, in a unit of millimeters (mm) of additional soil water needed to meet potential plant water demand. We calculated climate exposure as the change from baseline to future on a per-pixel basis, following the process described in detail in the works of

Thorne et al. (2016; 2017) [13,14], which combines the BCM's nine hydro-climate variables to define the climatic conditions occupied within each type of rangeland vegetation as noted above.

Climate exposure was then calculated as the change in each rangeland vegetation type relative to the historic or baseline conditions of any given vegetation type. The predicted climate of each grid cell was scored according to the frequency of historic baseline conditions. For example, if the expected climate in the future is beyond 80% of the frequency distribution of the historic climate values of any given set of grid cells within that vegetation type, the vegetation type was assigned a greater exposure ranking than 80%. Areas with an exposure score >90% were defined as "critically exposed" and areas where no current climate conditions are found in California in the future were defined as "non-analog". These, then, are areas where the vegetation is expected to have climates found only within 10% of the current dominant vegetation type range [24,25].

2.2. Assessing Climatic Water Deficit

Climatic water deficit (CWD) is a useful index for assessing plant water stress [23,26]. It is calculated by subtracting actual evapotranspiration (AET) from potential evapotranspiration (PET). PET is an index of evaporative demand, which is determined by the air temperature, while AET is limited by soil moisture that would be otherwise available for plant uptake. As such, CWD represents the difference between the amount of water a plant can potentially use for growth and development, and the amount of water it can actually use due to what is available for it in the environment. For example, if the CWD was determined to be zero, the plant would not be in a water-stressed situation. In this case then, the positive value of CWD indicates the water stress of a plant whose growth potential has not been fully met, and the higher the CWD values, the more severe the water stress for the plant ultimately is.

Using the BCM, the annual AET, PET, and CWD were obtained for the baseline period, and the BCM simulated the interactions of temperature and precipitation with landscape characteristics that influence patterns of vegetation assembly, including soil type, topography, and geology or parent material. Collectively, these determine the water balance of a particular watershed for any given period based on the grid cells in question. The baseline hydrological values were calculated by running the BCM using the baseline temperature and precipitation data inputs. We calculated future hydrological values under the climatic values of the two GCMs (i.e., CNRM CM5 and MIROC ESM). We then applied the 270 m^2 grid cell layer across California to spatially map baseline CWD, future CWD predictions, and the predicted change in CWD (i.e., future CWD minus baseline CWD).

We calculated the proportion of rangeland within each county rated as critically climate exposed (i.e., with a climate exposure rating of 90% or more) to assess how rangeland climate exposure might affect or influence livestock management operations and how such understanding might help to inform management options. We report the calculations for the thirty-five most climatically exposed counties in California as ranked by the MIROC model, while noting counties with the highest beef cattle inventories in 2017 using the "Cattle, Cows, Beef—Inventory" from the National Agricultural Statistic Service [27] as a proxy for the relative value of rangelands for beef production in each county and those with the greatest rangeland acreage. We used "Beef Cattle" as a straightforward index, but recognize that it omits some categories of cattle and does not capture the dynamics of moving cattle from one county to another.

3. Results

3.1. Climatic Water Deficit

Changes in future precipitation are difficult to quantify due to the degree of uncertainty in GCMs. However, projections for future temperatures show that increases across California have less spatial variability and, therefore, higher statewide CWD. The hotter temperature scenario (MIROC) also produces higher CWD (Figure 2), which agrees with the CWD trends and is also consistent with patterns detected and reported by Thorne et al. (2015) [19].

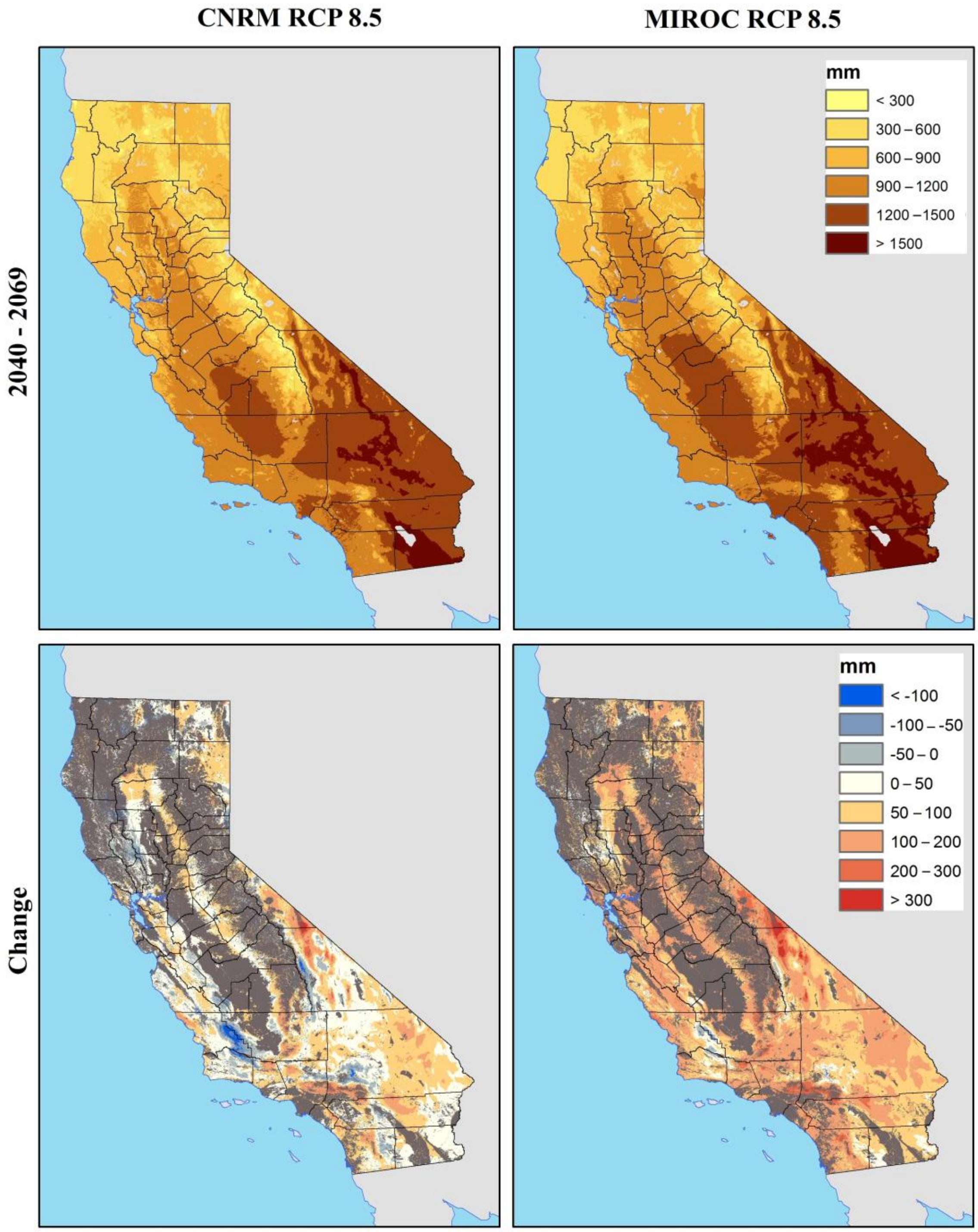

Figure 2. Projected total annual changes in climatic water deficit (CWD). We estimated future CWD using the CNRM and MIROC global climate models in the Basin Characterization Model. The two maps above show the projected future average CWD values statewide from 2040 to 2069, while the two maps below show the projected average changes from the baseline (1981–2010). The maps below focus specifically on the CWD changes in rangelands, with non-rangeland areas shaded in grey. In these figures, grey and blue tones indicate where plants' water stress is predicted to decrease in the future, and the warm colors indicate where it is predicted to increase.

However, the scale of change in CWD depends on the rangeland vegetation type in question and the specific climate model being applied (Figure 2). CWD increases in most rangelands in the state, which will result in increased plant water stress, alter competitive interactions, and alter forage availability and quality in the years and decades to come. In fact, water stress is expected to increase by at least 80% in each rangeland vegetation type by the mid-century period, or 2040–2069 when considering the RCP8.5. The desert shrub, shrub, and herbaceous rangeland (i.e., grasslands or prairies) vegetation types account for the largest portion of the total area of California rangelands, and are expected to experience increased water stress in both models.

3.2. Climate Exposure

It is important to note that the choice of which GCM model was used (CNRM vs. MIROC) did not change which vegetation type was typically "most" or "least" exposed. The extent of rangeland types in the top 10% of climate exposure ranges from 18–87% (Figure 3), indicating climate risk by the mid-century at least, according to the RCP8.5.

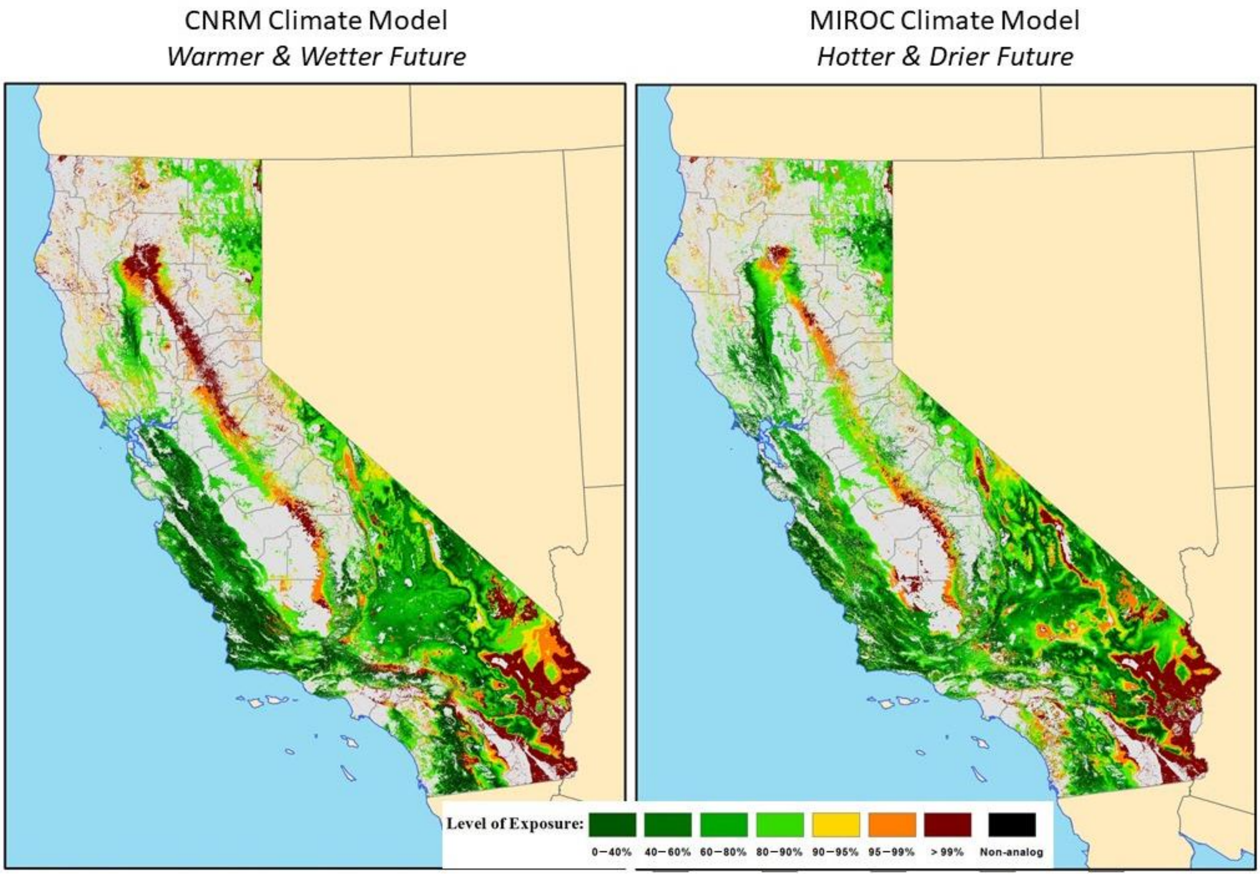

Figure 3. Climate exposure analysis maps of California rangelands, predicted by two climate models for the future climate of 2040–2069. The percentages of the legend represent the degree of climate exposure and were calculated based on the baseline climate within each vegetation type.

Geographically, there was a significant degree of variability in rangeland vulnerability (Table 1, Figure 3) as well. The Sierra foothills (e.g., Nevada, Placer, El Dorado, Calaveras Cos.) are expected to be highly exposed, and the two GCMs disagree somewhat on the location that will undergo the greatest impacts. Other high exposure rangelands include the northern end of the Sacramento Valley (woodland and herbaceous grassland in Shasta and Tehama Cos.) and the eastern parts of Southern California's inland and deserts, including San Bernardino, Riverside, and Imperial Cos. (mostly desert shrubs). Most of the Coast Range (especially the southern half) has low exposure on both models, while the shrublands of the High Sierra features had spatially varied exposure results; this may have implications for USFS rangeland allotments in areas that are not designated wilderness. Although spatially narrow, grasslands and shrublands scattered across the Northern California Coast (i.e., Del Norte and Humboldt Cos.) also have high exposure (see Table 1).

Table 1. The top thirty-five most exposed counties ranked by the MIROC model as it represents the locations expected to realize the greatest increase in CWD. Because California counties occupy, in some cases, broad geographic areas, there is no perfect means for organizing them geographically. However, below, the counties are grouped according to: Northern California coastal counties; the Northern California inland counties; the Sacramento Valley and foothill counties; the San Joaquin Valley and foothill counties; and the Southern inland and desert counties. Counties in bold font are those in the top 35 with the greatest number of beef cows, per the 2017 NASS data [27]. Those counties listed in italicized font are those that have the greatest amount of rangeland acreage, and those both bold and italicized met both of the aforementioned criteria.

County Name	Rangeland Acres	2017 Beef Cows	% High Exp, CNRM	% High Exp, MIROC
Northern and Central California Coast				
SAN LUIS OBISPO	1,866,859	22626	4.7%	10.9%
MONTEREY	1,710,264	21,257	54.9%	59.4%
MENDOCINO	400,991	**16,556**	91.8%	42.7%
HUMBOLDT	330,646	**17,412**	100.0%	99.9%
SONOMA	291,682	10,974	87.6%	15.5%
DEL NORTE	55,645	793	98.4%	100.0%
Northern California Inland				
MODOC	*1,588,850*	**34,625**	28.9%	31.9%
SISKIYOU	*1,027,102*	**26,188**	79.4%	63.1%
SHASTA	778,870	**16,342**	91.5%	66.0%
PLUMAS	261,707	8319	82.4%	54.8%
TRINITY	238,901	1707	98.0%	92.8%
SIERRA	131,664	3172	84.0%	53.0%
ALPINE	195,596	ND	87.6%	63.6%
Sacramento Valley and Foothills				
TEHAMA	*1,194,434*	***27,018***	85.1%	36.3%
BUTTE	349,327	6808	94.9%	88.9%
EL DORADO	291,034	3139	99.8%	82.2%
PLACER	205,792	8058	100.0%	84.5%
AMADOR	199,307	7518	95.8%	66.9%
SACRAMENTO	197,181	**13,934**	85.8%	15.0%
YUBA	162,252	6422	100.0%	93.4%
NEVADA	158,793	2183	99.3%	87.9%
SUTTER	68,309	3500	81.2%	25.1%

Table 1. *Cont.*

County Name	Rangeland Acres	2017 Beef Cows	% High Exp, CNRM	% High Exp, MIROC
San Joaquin Valley and Foothills				
FRESNO	*1,053,439*	***16,301***	47.6%	48.6%
TULARE	972,322	**72,778**	56.3%	52.1%
MARIPOSA	472,434	ND	54.9%	59.4%
MADERA	429,705	12,701	82.1%	82.1%
TUOLUMNE	406,485	4495	89.3%	56.0%
CALAVERAS	374,672	10,801	95.3%	62.6%
KINGS	204,963	4236	19.3%	64.1%
Southern California Inland and Desert				
SAN BERNARDINO	*11,826,727*	3679	41.9%	39.4%
RIVERSIDE	*3,539,618*	1504	58.0%	56.9%
IMPERIAL	*1,754,542*	ND	78.1%	82.8%
ORANGE	200,730	17	18.3%	74.2%
MONO	1,457,852	3700	36.7%	26.5%
INYO	5,961,182	9356	23.4%	28.1%

4. Discussion

Changes in CWD, climate exposure, and the level of livestock grazing at any given unit of landscape can help us understand how climate-mediated changes in vegetation will translate to the livestock industry. For example, the forage production potential in desert woodlands—which accounts for the largest area in the top 25% of exposure—is already relatively low, but will presumably be even less productive in terms of forage output in future years due to climate change and, relatedly, the role of fire, which is influencing shifts in vegetation systems not just in California, but across western arid landscapes. Hardwood woodlands have similar proportions of areas exposed to climate change, but they can provide more forage, thereby supporting a larger number of livestock, than desert woodland. Whether additional grazing pressure can be supported in hardwood woodlands is not clear. Many hardwood woodlands, such as the oak-dominated savannas in Southern and Central California, have experienced massive tree die-off events in recent years due to pest and pathogen pressure. One important climate-linked agent facilitating these die-off events is the gold-spotted oak borer (*Agrilus auroguttatus* (Coleoptera: Buprestidae)), whose distribution is increasing northward due to rising temperatures. This is important to note because there are other, and more difficult to predict, climate and non-climate mediate stressors and disturbances that will most certainly exert a force on the state's rangelands in the decades to come such as, in this aforementioned example, pests and pathogens. Therefore, the impact of climate exposure on the productivity of different vegetation types depends on the situation, even though the climatic exposure itself may be similar.

Consistent with climate stress for all-natural vegetation types [19], the wetter climate model, CNRM, projects a more moderate increase in rangeland vegetation's CWD across much of the state; conversely, the drier climate model, MIROC, projects a substantial increase in CWD, including across some historically significant cattle-producing areas such as the Central Valley and Sierra foothills (see Table 1). Both models predict the largest increase in CWD in the eastern Sierra Nevada and the Transverse Ranges. The most notable increase in CWD is in desert shrub rangelands in the south of Mono and northern Inyo counties, both of which are located under the rain shadow in the Sierra Nevada and are distant from coastal influence, which otherwise ameliorates higher temperatures or heatwaves. This is important in this part of the state because livestock is the top-ranked agricultural product in these counties, accounting for 49% and 50% of their agricultural revenue, respectively [28], so while these counties are not the most productive lands for cattle, the expected impacts will be felt significantly if current climate trends continue in the years to come.

Shrub or herbaceous rangelands in counties with high stock of cattle, such as Modoc, Monterey Cos., and portions San Luis Obispo Co., are likely to have increased CWD, and this is especially the case for the eastern and more arid portions of San Luis Obispo Co. CWD is expected to increase to moderate levels, with a slight increase in the Sierra foothills, which are dominated by herbaceous and hardwood woodland vegetation. Similarly, Tehama County—at the eastern foothills of the Coast Range and at the western foothills of the Sierra Nevada—will experience water stress in its shrub, herbaceous, and hardwood woodland vegetation. In addition, some very large wildfires and fires that have burned at high severity have impacted vegetation patterns in many portions of the Sierra foothills. The coupled role of wildfire activity in climate stress will certainly play out across California's vegetation systems, including rangelands. In fact, wildfires that burned at high severity are promoting significant type changes in vegetation systems across the western United States.

The impact of the increase in CWD on overall rangeland vulnerability is not fully understood. This is because different vegetation types have different levels of sensitivity to water stress [13] depending on the total rangeland acreage each type comprises (Figure 1) and their relative level of use by ranchers. This is also likely a function of current and historical land use patterns that can influence the level of sensitivity that vegetation has to water stress. Thorne et al. (2016) [13] found that desert shrubland was significantly less sensitive to water stress than other vegetation types, despite accounting for the largest proportion of total rangeland area affected by the increase in CWD (Figure 3). For example, desert shrubs may respond more easily to increasing water stress [29]. In contrast, herbaceous vegetation is considered sensitive to precipitation. Although grassland areas are relatively smaller in area, they are highly productive and have great overall importance as a feed source for California livestock [6,30].

Since CWD is based on biophysical relationships that are caused by environmental factors, changes in CWD can have physiological relevance to rangeland vegetation. CWD can potentially be used to predict plant growth and water stress, both affecting forage availability and sustainability in the California ranching industry. Accurately modeling future changes in forage availability has not yet been comprehensively conducted for California rangelands [31]. Although warming temperatures can have a direct impact on livestock health [32] and crop production, this study did not take into account the direct temperature impact. This is because water source availability is typically the key factor limiting the productivity in Mediterranean-climate grasslands [33].

5. Conclusions

Model projections at management-relevant scales can help ranchers and rangeland managers adapt to climate change. Understanding the likely vulnerabilities of livestock production operations in different geographic areas provides context that aids when considering what adaptation strategies are the most appropriate and will help in the development of programs and policies to maintain the viability of the ranching industry in California.

California ranchers have much experience dealing with drought and other unfavorable climatic conditions, and they already possess a toolbox of proactive adaptations—such as stocking conservatively and resting pastures—and reactive adaptations, such as reducing herd size, providing supplemental feed, and moving livestock to another location [34]. However, with longer-term changes in climate and vegetation, the current toolbox may need to be expanded. This is a critical point, as climate changes are projected to accelerate in future decades even beyond that which we have already experienced. Briske et al. (2015) [35] suggest that switching types of livestock, introducing novel plant species, and supplementing with alternate income, such as ecosystem services payments, may become increasingly necessary in Western rangelands. Focusing policy attention on landscape-scale risks, such as entire counties or regions in danger of losing a large fraction of their livestock revenue, can help compensate for the negative effects of climate change (e.g., by offering education on adaptation strategies and incentives for alternative livelihoods).

Because California rangelands occupy such diversity in their vegetation types and extend across the most mesic to xeric conditions, there are opportunities for broader scale applications relating to soil health, water management systems, and potentially, managed aquifer recharge. California has a long history of water scarcity. With recent state policy measures, including the Sustainable Groundwater Management Act, local water management jurisdictions will be required to adhere to water budgets. Rangelands could be good opportunities to explore the compatibility between livestock management and managed aquifer recharge.

More research is needed on the biophysical aspects of climate change on California rangelands, such as the relationship between CWD, climate exposure, vegetation type shifts, and forage productivity. More research is also needed on appropriate adaptive management responses to biophysical challenges on rangelands, including those with no analog under current conditions. An area of research that also merits attention is related to the socio-ecological and socioeconomic implications that a changing climate may have on agriculturally dependent communities, especially those traditionally underserved or considered vulnerable.

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Data Availability Statement: The datasets generated and/or analyzed during the current study related to cattle numbers and rangeland land area are based on publicly available data retrieved from the USDA National Agricultural Statistics Service and the CAL FIRE Forest and Rangeland Assessment Program (see Stewart et al., 2003 [30] and Ferkovich et al., 2017 [6] for access). Hydrological input values were obtained from BCM outputs, and climate projections are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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