ASSESSMENT OF CALIFORNIA CROP AND LIVESTOCK POTENTIAL ADAPTATION TO CLIMATE CHANGE

A Report for:

California's Fourth Climate Change Assessment

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PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report advances the understanding of climate change challenges facing California agriculture and how it is likely to adapt to those challenges, focusing on Central Valley crops, the dairy industry and the beef cattle grazing industry, which together comprise the great majority of farm value in California.

ABSTRACT

California agriculture has been characterized by rapid innovation and adaptation to water, markets, and regulations. Climate change poses challenges to agriculture in California as gradual warming reduces snowpack and requires shifts in where crops are grown. Moreover, extreme events including droughts and floods can increase in frequency, duration, and intensity. This research examines the potential adaptation of agriculture to climate change and its economic impacts by mid-century. Three subsectors - crops, dairies, and beef cattle - are analyzed considering historical and projected climate change scenarios, and the potential effects on crop yields are reported. Shifts in the spatial pattern of agricultural land, technology, and demand for California agricultural commodities are considered in the analyses. A deductive approach (mathematical programming) was employed to estimate adaptation to climate change via cropping patterns, water, and land use. For the most part, modeling results indicate that the crop sector remains robust, with water shortages similar to those in recent droughts particularly in dry years. We found that the potential overall impacts of climate change on crop yields, total production, and revenues relative to current conditions are likely to be less than other impacts such as changes in water supply, conversion of agricultural land to other uses, technological adaptation, and market demand for California crops. Change in climate-related yield and its effects on overall crop production are of lesser magnitude than effects due to loss of water supply and conversion of agricultural land to other land use classes. Markets demanding higher value California commodities may contribute to a concentration of the agricultural value per unit of area and water. The future of feed crops is uncertain as competing water uses on other crops or economic sectors will drive water opportunity costs high. Substitution away from silage corn, irrigated pasture and alfalfa in the dairy cow and beef cattle diet, and an overall decrease in the dairy herd may occur as an adaptation. Protection of groundwater from further overdraft and flexible exchange of water among users may greatly improve the prospects for agriculture in weathering future extreme events.

Keywords: Agriculture, Dairies, Livestock, California, Climate Change, Adaptation, Economic Impacts

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HIGHLIGHTS

- Potential crop adaptation in irrigated areas, applied water, crop selection, and water use intensity were examined under various climate scenarios. Modeling results for crops are in line with previous findings for California and elsewhere, in which net returns for farming are maximized by adapting crops and use of production factors. Specialty crops prevail over feed, field and grain crops, posing challenges for some dependent sectors such as beef cattle and dairies.
- Under the four downscaled climate scenarios analyzed, no significant water shortages to agriculture were identified. However, the 30% water shortage scenario does have an effect on irrigated areas, water use, cropping patterns, and gross revenues. Availability and protection of groundwater reserves for use during dry years is crucial to avoid larger farm economic losses.
- Dairies will face challenges to obtain forage due to increasing water competition among crop groups and the lower returns to hay and corn silage per unit of water. Strategies, including reduction of the milking herd and finding alternative sources of forage at the expense of reduced dairy yields per cow, may be adopted. Direct heat stress is likely to have only small impacts.
- Increases in available grazing areas in the foothills and mountains during the late fall, winter and early spring may result in improved California grazing opportunities in future years. In contrast, a decline in irrigated pasture in the Central Valley floor will challenge further expansions of the beef cattle sector.

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1: Introduction and Background

1.1 California Agriculture and Climate Change

California's agricultural powerhouse produces more than 400 commodities and supplies the bulk of the fruits, nuts, and vegetables in the United States. Produce from California ranks first in value nationwide, with $47 billion in cash receipts in 2015. The commodity list is led by milk production, which contributed 7.1% of the United States' total value of livestock and livestock products while crops contributed to 15% of the nation's total value of crop production in 2012 (USDA. ERS. 2018. USDA. Census of Agriculture, 2012).

The state suffers from disconnects between water supply and demand, both in space and time, which relate directly to its Mediterranean climate and geographic diversity. Most of the state's precipitation occurs during the winter months in the northern region and the Sierra Nevada, while demand is the highest during the drier months (May through September) in the Central Valley, and in the highly populated areas on the coast and in the southern region of the state. The state is also subject to widely-varying hydrological conditions, which include various multi-year droughts in the nearly 110 years on record. California has overcome these challenges by building one of the most advanced, progressive networks of reservoirs and canals in the world, which is capable of storing and moving water north to south and to the coasts to meet water demands. Thus, California's Central Valley, the largest agricultural production region in the state, relies on natural precipitation cycles, highly advanced engineered waterways, and large ground water aquifers to meet summer water demands for agricultural production.

Climate change impacts are projected to affect regions all over the world and while many studies to date are concerned with localized climate change impacts on agricultural production, it is important to keep in mind that having a holistic perspective of climate change impacts in the state is of importance (Lee and Sumner, 2015). Climate change scenarios predict higher temperatures, and some of these scenarios project increased rainfall, and decreased snowfall, altering the current pattern of water storage and irrigation availability (Pathak et al., 2018; Van Lienden et al., 2014). Weather events are projected to increase in severity and variability (Berg and Hall, 2015; Dettinger, 2011). Potential effects of climate change include an overall decrease in California's surface and groundwater supplies (Connell et al., 2012; Dogan, 2015; Singh, 2015), changes in crop yields, and alteration of crop irrigation requirements. This potential issues will likely catalyze adaptation of agriculture, particularly to drier and warmer conditions (Howitt et al., 2015; Lee and Sumner, 2015; Medellín-Azuara et al., 2012; Connell et al., 2012; Jackson et al., 2011). Conditions for growing specific crop categories under climate change conditions may vary widely by geographic location (Mehta et al., 2013).

Adaptation studies for Europe and Africa discuss vulnerabilities and potential adaptation of crops and livestock farming decisions in such regions (Van Passel et al. 2017, Soe and Mendelsohn (2008). Sectors dependent on crop agriculture, including dairies and beef cattle, will be directly and indirectly affected by climate change. Warmer temperatures may raise the snow line in the foothills, changing grazing opportunities for cattle. Simultaneously, competition for water among a wide range of crop commodities, cities, and environmental and other water requirements may compromise the availability of water dedicated to crops like alfalfa, silage corn, irrigated pasture, and other forages.

In this research, we examine the potential for California crop agriculture to adapt to the projected effects of climate change on water availability and crop yields by mid-century. The effects of conversion from agricultural land to other uses, including the enhancement of the urban footprint, are also considered. Lastly, the potential role of markets and technological adaptation in crop agriculture (e.g. breeding, cultural activities, and harvesting) considering historical trends is factored in. We also examine the potential impacts on dairies and beef cattle as supply for forage crops and grazing land changes in response to markets for agricultural commodities, warmer climate, climate-related water availability, and shifts in regulatory and other conditions.

1.2 Modeling Agriculture Impacts Under Climate Change

Understanding climate change effects on agronomics began in the early 1990s *(*Adams et al., 1989; Adams et al., 1990; Reilly et al., 1993; Adams et al., 1995) through the use of inductive (i.e. statistical) and deductive (i.e. process-based modeling, empirical) approaches for analyzing the economic repercussions of climate change on agriculture. Inductive methods observe statistical relationships between climate or weather trends and crop yields, while deductive methods use models to simulate the biological processes of crop growth and climate change implications on these biological mechanisms (Moore et al., 2017). A number of studies have compared the results between process-based models and statistical model methods for individual crops in specific locations (Estes et al., 2013; Holzkamper et al., 2015; Liu et al., 2016). Other studies focus on multi-crop sensitivities to climate impacts (Lobell and Asseng, 2017; Knox et al., 2016; Knox et al., 2012; Roudier et al., 2011).

Statistical approaches allow for the linking of climate or weather trends to crop yield outcomes through the use of observation data at farm- or regional-levels and account for implicit farmer management behavior that is not accounted for in process-based modeling approaches (Roberts et al., 2017). A disadvantage of this approach is that it imposes the same mean values throughout all the locations leading to an amplification of measurement error, since interpolated data already include measurement error (Moore et al., 2017; Auffhammer and Schlenker, 2014). Another general disadvantage of using a statistical approach is that often it does not account for the effects of CO_2 increases (Lobell and Asseng, 2017; Boote et al., 2013) nor does it consider reduced form relationships between weather or climate variables and crop yields when using future climate change projections (Moore et al., 2017).

Optimization models are a set of deductive approaches that employ a theoretical programming formulation to implementing bottom-up biological processes, parameters that have been established through laboratory experiments, and can be externally validated to provide prediction and adaptive techniques that allow for the linking of relationships between weather and agricultural crop yields (Roberts et al., 2017; Lobell and Asseng, 2016; Moore et al., 2017). An advantage of using a deductive approach is that the implemented techniques incorporate many options for substituting other resources for water and result in high elasticity of the crop price (Scheierling et al., 2006). While many deductive crop production modeling schemes neglect adaptation techniques taken by farmers, previous models have bridged this gap by focusing on decision-based adaptation responses such as crop choice (Seo and Mendelsohn, 2008). Results of such models indicate reductions in economic impacts due to climate-related factors of up to 25%, demonstrating the importance of incorporating adaptive decision-making to improve upon model accuracy. However, in Europe, a study by Van Passel et al. (2017) found a span from +5% to -32% in yields with a predominantly negative effect. The use of a deductive approach in the analyzation of climate change effects on agriculture can provide insights on the future of agriculture globally and provides implications for future water management in all sectors.

This study employs a deductive approach using a version of the Statewide Agricultural Production Model (SWAP) (Howitt et al., 2012) following the methods described in Medellín-Azuara et al. (2012). SWAP is an optimization model calibrated by Positive Mathematical Programming (PMP) (Howitt, 1995), to estimate the economic effects of climate change on agricultural production in California. Although there are some limitations to a deductive approach, previously described, this approach has proven itself well suited for a regional scale economic impact assessment of climate change effects on agricultural crop production. The approach employed in this report updates and expands the work of Medellín-Azuara et al. (2012) in several ways, by: 1) including five water availability climate scenarios; 2) revising crop yield response to climate change; 3) exploring potential changes in crop water requirements; 4) updating projections on crop demands for crops produced in California; 5) considering land conversion from agriculture to other uses; and 6) exploring yield-growth trends. In addition, we evaluate the prospects for livestock, which constitutes about a fourth of all agricultural value in California.

Figure 1 below illustrates the modeling framework. A base set of inputs to irrigated agriculture including land, water, labor, and supplies along with cost, crop yield, and price information (left box) is employed to calibrate agricultural production functions per crop and region (middle box) using positive mathematical programming (Howitt, 1995). Hydrologic, economic, and yield effects and resource constraints are then considered in the calibrated model to estimate cropping patterns by considering the crop portfolio that will maximize net returns to land and management given the limited land and water resources (right box).

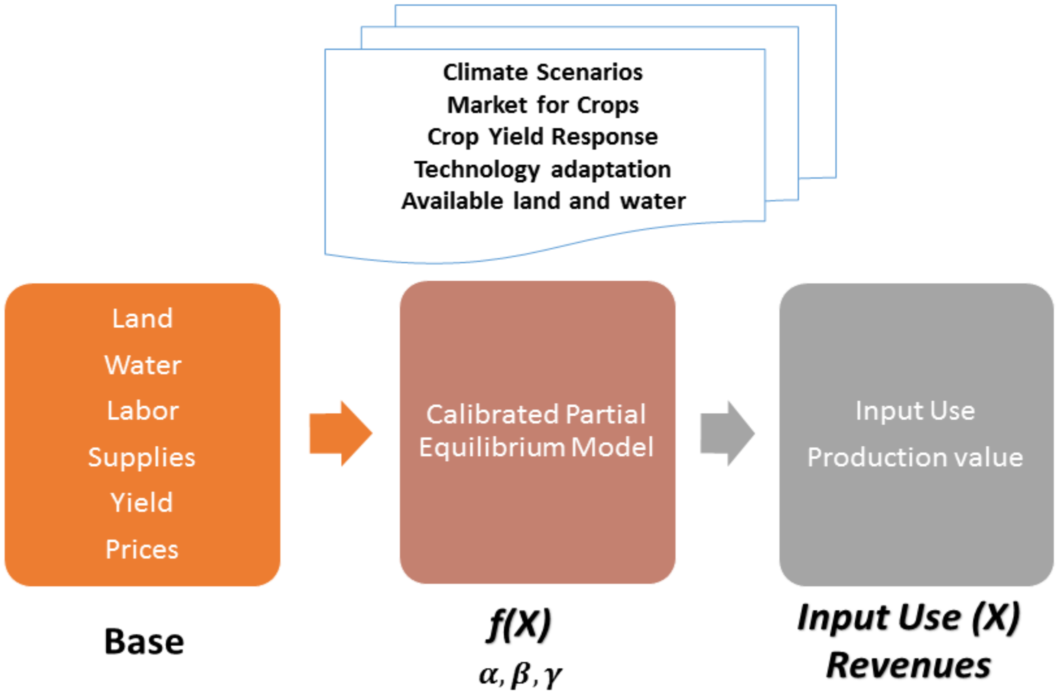


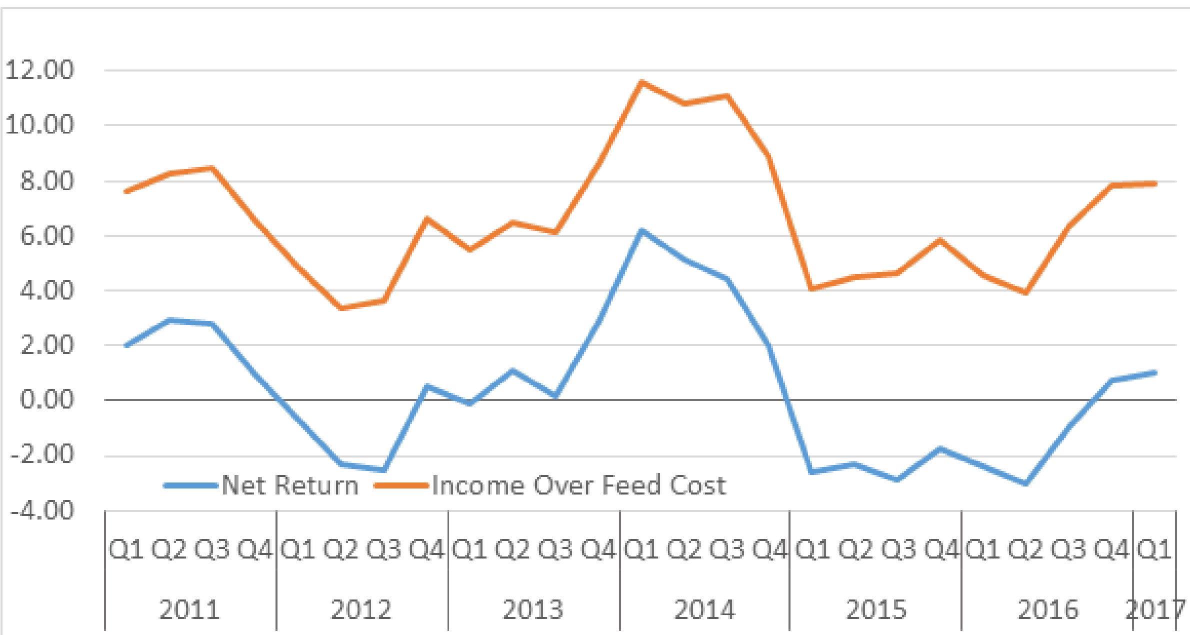
Figure 1. Modeling framework for crop production under historical and climate conditions. The orange box on the left represents calibration (base) inputs for agricultural by region and crop group (Figure 4). The middle box represents a calibrated model and the top box the factors affecting production by mid-2050. The grey box at the right represents cropping patterns and production input use by region with 2050 conditions applied to the calibrated model.

1.3 Potential Climate Effects on California Dairy and Beef Cattle

Understanding the impact of climate change on the California dairy industry is complicated by the fact that global milk and grain prices varied dramatically from year to year between 2007 and 2017. An index of dairy feed prices set equal to 100 for 2011 rose to almost 150 during the Midwest drought of 2012 and varied between 20% to 50% higher than 2011 through 2014, before declining to mostly between 10% to 30% above 2011 during 2015 to 2017. However, even in this period of lower feed prices overall, the index of dairy concentrate feeds was more than 40% above 2011 in the summer of 2016. Similarly, milk prices rose from a low in 2009 (about $11 per hundred weight for a few months), to moderate prices in 2010 and 2011, before collapsing in 2012, and then reaching record highs of over $22 per hundredweight for much of 2014, before collapsing at the beginning of 2015 and remaining low ($14 to $16 per hundredweight) through 2017. With such high prices in 2014, California dairy revenues were at record high levels during that year. Net revenue was high despite the pressure on hay and silage prices from drought-reduced crops.

We can consider the main effects of climate on dairy by examining data for dairy farms in the South San Joaquin Valley, where most California milk is produced. The price of alfalfa hay used by these farms rose from a low of about $200 per ton at the beginning of 2011 to $300 per ton in the summer of 2014 when milk prices were high and hay availability was low. The price of alfalfa hay then gradually fell back to $200 per ton at that end of 2016. The price of silage fell from $52 per ton in 2011 to $40 per ton in 2012 before jumping to $61 per ton in 2014 and dropping to $50 per ton in 2015 when milk prices were low.

There is no obvious climate-induced trend in hay or silage price because price swings are dominated by short-term weather events, the gradual shift of acreage to tree nuts on the supply side, and the lack of increase in the price of milk or the number of cows on the demand side. The California dairy industry faced economic strain over the past decade after years of economic returns that spurred rapid growth. Milk price and feed price pressures along with regulatory costs are behind the California economic distress. Low global milk prices, exacerbated by high grain prices in 2009 and 2012, have been the most problematic issue. These low milk prices continued through 2017. According to Figure 2, high hay and silage prices in 2014 reduced economic gains during that high milk price year. Expansion of acreage in 2017, although small as a share of total acreage, was encouraging that more hay acreage may return in the fall of 2017. Silage also expanded in 2017, indicating that silage demand from the dairy industry remains strong.



Source: CDFA Marketing Services Division, Dairy Marketing and Milk Pooling, Cost Comparisons and Cost of Production Feedback Data.

Figure 2. Net Return and Income over Feed Cost in the Southern San Joaquin Valley

Milk cow numbers have been declining gradually for a decade to about 1.7 million head in 2017 (Figure 3). Over the same period, milk per cow was slightly higher and milk production initially increased before declining with lower milk prices after 2014. This result has been a consequence of competitive economic pressures and regulatory pressures. At the same time, the industry has consolidated into some of the hottest and driest counties in the San Joaquin Valley.

There is very limited evidence that a warmer climate in the summer may cause significantly lower milk production per cow, other things equal. The one relevant study using national data is from USDA economists. Depending on the climate model used, the results of Key and Sneeringer (2014) imply that the additional heat stress caused by global warming could reduce milk production for the average U.S. dairy by approximately 0.60% to 1.35% per year in 2030, with somewhat larger declines predicted for dairies in the southern states. For their central scenarios, the impact of California for 2030 is 0.5% lower productivity. These are tiny impacts compared to the very large effects on forage prices and availability that are likely to occur.

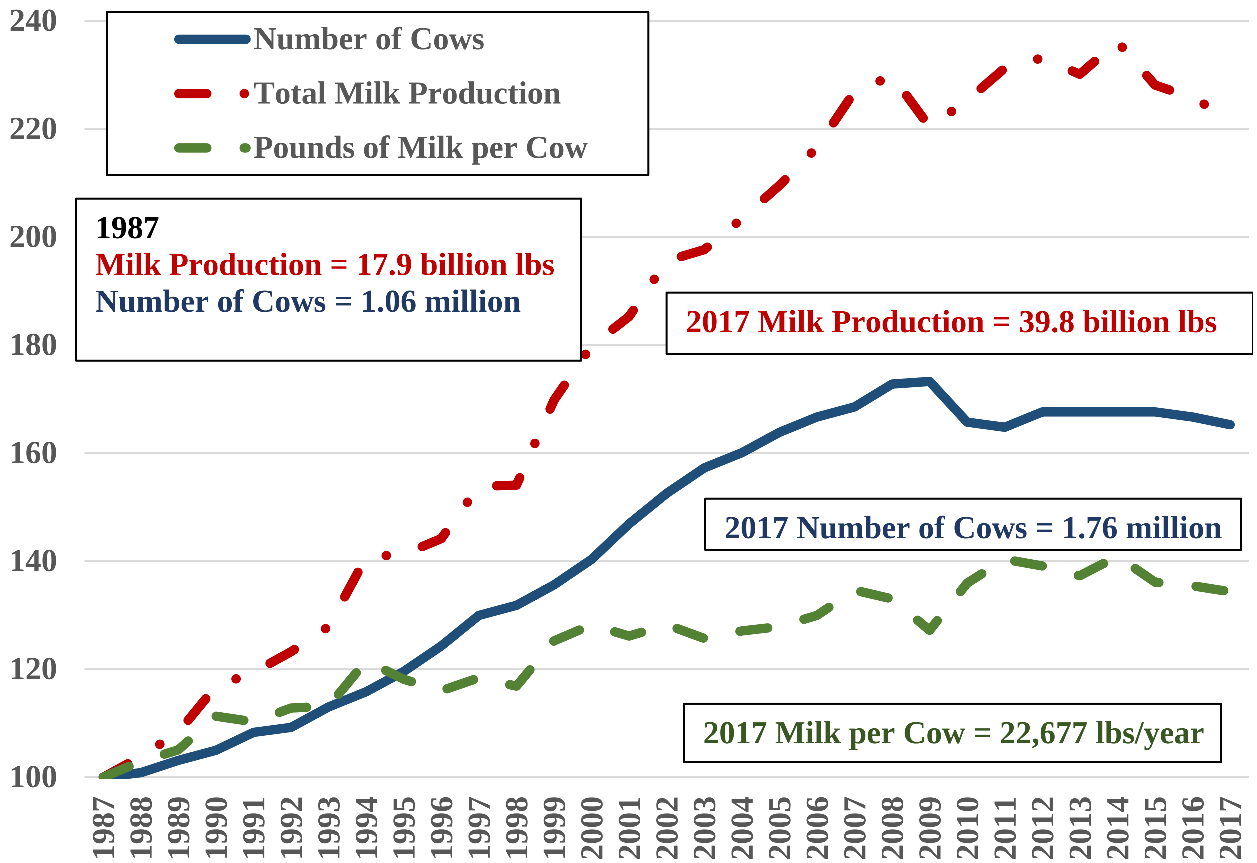


Figure 3. California Milk Production and Productivity Indexed to 1987

The remarkable end to growth in the California milk production a decade ago has major implications and it is crucial to understand the degree, if any, to which this change is due to climate, climate regulation, or other causes. Wei (2018) studied the costs of California dairy farms in the context of environmental regulations and finds that econometric evidence indicated that air quality regulations have not raised farm costs significantly.

1.3.1 Modeling Forage Supply for Dairies

Hay is produced throughout California from Imperial County (about 15% of production) to the far northern counties (another 15% to 20%). About half of California hay is produced in the San

Joaquin Valley. Silage is concentrated near the vast majority of dairy cows in the San Joaquin Valley, with about 40% of acreage in Tulare County alone. Corn silage area in California fell from about 480,000 acres in 2011 to about 320,000 acres in 2016 before climbing to 360,000 acres in 2017. California forage acreage by class is presented in Table C-1 and Figure C-1 of Appendix C.

1.3.2 Modeling Feed Supply for Beef Cattle

The California beef cattle industry is the second largest livestock sector in California, following dairy cattle. The production of pasture for grazing is linked closely to the beef cattle industry in California. At the early stage of the beef production cycle, pasture production for grazing greatly influences the beef cattle industry. The beef cows feed from grasslands and give birth to and provide milk for calves. Ranchers sell weaned calves and keep some as replacement heifers or as stockers, depending on the forage conditions and availability on the rangeland. Weaned calves grow on pasture until they are mature enough to be fattened in feedlots. A stocker operation, which owns or leases pastureland, purchases feeder cattle from the market and sells the cattle with a desired weight at the end of the grazing season. Sometimes cow-calf operations keep weaned calves when pasture production is sufficient for stocker production. Ranchers may feed hay to stockers when the weather conditions are not conducive for enough pasture production.

Cattle are placed in feedlots after grazing to rapidly gain weight. Corn and oilseeds (soybeans) are the predominant feeds. Other grains used include oats, barley, sorghum, and by-products. Feedlots are concentrated in areas with large production for corn and other grains, such as the Great Plains, some parts of the Corn Belt, Southwest, and Pacific Northwest. For beef production, slaughterhouses purchase the fed cattle and cull cows and bulls for beef product. Slaughterhouses also purchase cull dairy cows for beef. There are relatively few feedlots in California compared to the supply of calves and feeder cattle.

Modeling the impact of climate change on the California beef cattle industry is complicated by the fact that beef cattle production relies greatly on pasture production on California's abundant rangeland, which is comprised of heterogeneous sites with very different biophysical characteristics and climates. California climate change affects the beef cattle industry by influencing pasture and feed crop production. Studies show that evenly distributed precipitation patterns during pasture growing season favor grassland production (Duncan and Woodmansee, 1975; Lauenroth, 1979; Dukes et al., 2005). In addition, research found that the atmosphere carbon dioxide concentration level and air temperature affect the aboveground biomass on pastureland (Dieleman et al., 2012). Pasture yield also depends on the biophysical environment such as soil type, elevation and slopes. In response to short-term variation in pasture availability due to weather variation, operations will manage herd size by selling cull cows and bulls to reduce the herd or purchasing new yearling heifers to expand the production. In the steady state scenario under climate change, the operations replace cull cows with replacement heifers at a stable rate. The replacement heifers are obtained from the operation's own yearling heifers or are purchased from the market.

Pasture-hay Ratio and the Amount of Grazing and Forage Consumption by Beef Cows

Hay production is also closely related to the beef cattle industry. Ranchers may feed stockers hay when the weather conditions are not sufficiently conducive for pasture production. Based on the UC Davis Cost Study of cow-calf operations (Forero et al., 2017), a typical cow-calf operation with 300 beef cows consumes 60 tons of hay to supplement cattle feed during certain time periods within a year. According to George, Frost, and McDougald (2016), one animal unit month (AUM) is about 26 pounds of dry forage per day for 30 days. Thus, hay supplies about 154 AUMs for the operation, which has 300 beef cows, 60 yearling heifers, and 15 bulls with the exact numbers of animals changing throughout the year.

Based on the number of monthly animals reported by the cost study (Forero et al., 2017) and the reported average AUMs consumed by beef cows (1.2 AUMs), bulls (1.3 AUMs) and yearling heifers (0.7 AUMs) from grazing, beef cows consume about 4,063 AUMs from grazing in a year. This total constitutes about 85% of total AUMs from the herd including bulls and heifers. If we assume beef cows consume about the same portion of the hay in the cow-calf operation, the beef cows consume about 131 animal unit months (85% of the 154 AUMs from hay). Thus, the annual pasture and hay ratio for beef cows is 1:31, i.e. 1 AUMs from hay and 31 from AUMs from pasture.

2: Methods

In this section, we provide detail on the modeling approaches employed for crops, dairies, and beef cattle grazing including the modeling assumptions under historical and climate change conditions in California.

The regions of the agricultural crop model shown in Figure 4 are aggregated into four supra regions, namely: (1) Sacramento Valley, the Delta and East of Delta, (2) San Joaquin Valley, (3) Tulare Lake basin, and (4) all other areas (shown as expanded coverage) which include the Central Coast, the South Coast, and the Colorado River region in the South East corner of the state. Likewise, the results for the 20 DWR crop groups are aggregated into 4 crop groups, namely: feed crops, field and grain, fruit and nut trees, vegetables, and non-tree fruits. Employed projections of land use, technology, and crop markets are assumed to be independent of climate conditions by 2050. Changes in crop yields were generic for warmer and drier forms of climate change due to the lack of crop yield response studies for each of the analyzed climate scenarios. Lastly, water shortages from the CALVIN model by climate scenario were incorporated in the agricultural model optimization.

2.1 Modeling Crop Production Under Historical and Climate Change Conditions

The SWAP agricultural production model (Howitt et al., 2012) was adapted following the approach in Medellín-Azuara et al. (2012), and recent studies to quantify the economic impacts of the 2012-2016 California drought. Medellín-Azuara et al. (2015, 2012) present a full formulation of the model, yet this report will describe the modeling assumptions employed for this study. Figure 4 provides a map of the agricultural model coverage for agriculture in California, representing more than 85% of the irrigated area statewide. Three major basins are identified in the Central Valley, namely the Sacramento River Basin, the San Joaquin River Basin – including the Delta and east side agriculture – and the Tulare Lake Basin. Other areas in the state in the model include the Central and South Coasts, and Inland southern California areas such as Imperial, Palo Verde, and Coachella. The model uses irrigated area and water use information for a set of 20 crop groups following the California Department of Water Resources classification for 2010, the latest year available at the time of this study representative of a non-dry year. Crop price and yield information was collected from the NASS county agricultural commissioner reports, and cost information was determined from the UC Cooperative Extension cost and return studies. Details on data sources are provided in Howitt et al. (2015). The full set of crop categories are alfalfa, almonds, pistachios, corn, cotton, dry bean, tomato (fresh and processing), cucurbits, safflower, onion, garlic, potato, rice, sugar beet, vine, along with aggregates of all other field, vegetables, grain, and orchard crops. Baseline irrigated area, water use, and gross revenues are presented in Table 1 below.

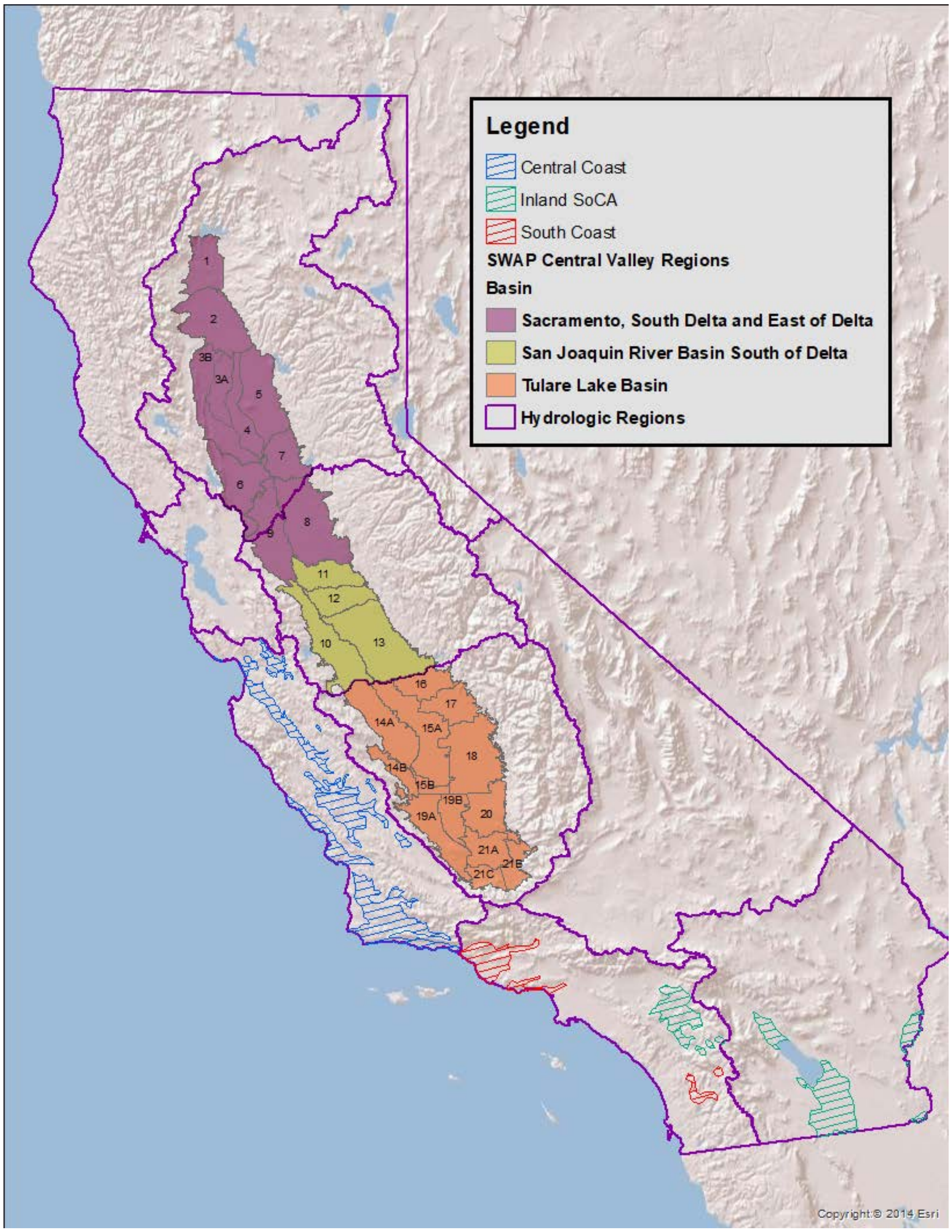


Figure 4. Coverage of the agricultural production model in the Sacramento, South Delta and East of Delta (purple shading), San Joaquin River Basin (yellow green shading), and Tulare Lake Basin

(orange), as well as expanded coverage in the Central Coast (hashed blue), Inland Southern California (hashed green), and South Coast (hashed red).

Table 1. Base (2010) irrigated crop area, agricultural water demand, and gross revenues.

Region	Base Irrigated Crop Area (1000 Acres/year)	Base Agricultural Water Demand (TAF/year)	Base Revenues (Million $2010)
Sacramento River, Delta and East of Delta	2,243	7,184	7,028
San Joaquin River Basin	1,620	4,934	5,444
Tulare Lake Basin	3,073	9,789	13,805
Other	1,512	4,448	19,320
Total	**8, 447**	**26,354**	**45,597**

To study the impacts of climate change by 2050, both non-climate related and climate-related factors are considered. Non-climate related factors include the change in the agricultural footprint based on current trends, technological adaptation, and crop market demands. Climate related factors include changes in crop yields due to temperature and changing atmospheric carbon concentrations and changes in water supply and allocation due to a changing climate. These factors are shown in the upper box in Figure 1 above. Various studies also indicate that irrigation requirements might change (Shoups et al., 2010; Mehta et al., 2013; Deryng et al., 2016), yet the results for California seem mixed with both increases and decreases in water use within a few percentage points with respect to current conditions. Hence modeling in this report considers no increase in irrigation requirements for California crops.

2.1.1 Agricultural Footprint

The dynamic mosaic of agricultural land in California is likely to face challenges of urban growth, economic development in other sectors, and competing water demands which can make water supply less reliable in some areas. Following the recommendations from the Fourth Climate Assessment, the LUCAS model from the USGS (Sleeter, n.d.) was employed to estimate conversion from agricultural land into other land use classification in each of the agricultural model regions (Figure 4 above). The research team conducted geostatistical analysis using the rasters of the LUCA model under business as usual and medium growth. Ten iterations for annual and perennial crop agriculture between 2010 (the base year of the agricultural model) and 2050 were averaged and compared. The change in the agricultural cover area was then applied as a constraint on land use to the agricultural model. Statewide, a reduction of 5% of the existing agricultural land (8.5 million acres) of all areas included in the agricultural model is expected. Unlike previous projections of mostly loss of agricultural land, there are some areas north in the Sacramento Valley and in the San Joaquin Valley, close to the foothills, that might see some small increase in agricultural use. Also, some agricultural areas in the coast might see an increase in the irrigated area of perennials. The Tulare Lake region area may lose about 8.5%

of its current irrigated area. The largest reduction in agricultural area (22%) may occur in the South Coast, which hosts most of the state's population. Central coast agriculture and south inland agriculture may lose roughly 4% of the currently irrigated area according to the LUCAS model projections. Agriculture in the foothills in areas outside of the agricultural production model might increase by 40 thousand acres from the currently existing 58 thousand acres, mostly located in the Sierra foothills. The economic effects of these expansions are not evaluated in this study.

2.1.2 Technological Adaptation

Crop yields have substantially increased over the years in California as a result of mechanization, improvement in cultural practices, improvement in crop varieties, and other factors. Brunke et al. (2005) quantifies crop yield changes for major crop categories in California and provides the basis for projecting crop yields into the future. Medellín-Azuara et al. (2012) incorporated the projected 2005 to 2050 increases in yields based on Brunke et al. (2005). In this study, these estimates were revisited for crops like tomatoes and orchards as their relatively high historical yield growth rates are due to changes in irrigation, which is nearly complete for most land in California. Overall, technological improvement is expected to increase yields by an average of 24% for all crops between 2010 and 2050.

2.1.3 Demands Facing California Farm Commodities

The main factors affecting commodity production in California are demand shifts and price elasticity of demand, or the ability of prices to resist demand shifts. Price elasticity is primarily determined by the share of California crops in the overall market, along with the ability of crops to substitute for others in that domain. The relevant market for a crop depends on seasonality and transportation factors; some crops have a world market while others have a more localized market. Crop substitutability depends on the type and purpose of the crop, with some groups having greater substitutability than others. Overall commodity demands increase with both population and income growth; however, these factors are primarily relevant in larger time scales. Demands of specific crops are linked to factors relating to the market-use of the crop. For example, because alfalfa hay and silage corn may be heavily used as dairy cattle feeds, demand is largely a function of the dairy market. More information on demand and price elasticity can be found in Appendix A.

2.1.4 Water Supply

The SWAP model has a long history of applications in California, including climate change, salinity, and drought (Medellín-Azuara et al., 2012, 2008, 2013, 2015; MacEwan et al., 2016). The SWAP model was initially ancillary to the CALVIN water supply model (Draper et al., 2003), providing shadow values of agricultural irrigation water by basin in the Central Valley and the Colorado River hydrologic region. The CALVIN model allocates water monthly over an 82-year time period among agricultural, urban, and environmental uses such that the total cost of water shortage and systemwide operation is minimized. Applications of the CALVIN model to study climate change in California include Tanaka et al. (2006), Medellín-Azuara et al. (2008), Connell et al. (2012), Sicke et al. (2013), and Dogan (2015). The team of Herman et al. (2018) is producing a report using CALVIN for this Fourth California Climate Assessment with some improvements with respect to previous versions of the model, including additional climate scenarios, revised 2050 water demand projections, and updates in the groundwater model based on C2VSIM (Herman et al. 2018).

The CALVIN model provides monthly time series of water deliveries to agriculture, which may include months with cutbacks. These cutbacks are particularly impactful in dry years, due to higher opportunity costs in other uses including urban, environmental flow requirements, or operational restrictions such as Sacramento-San Joaquin Delta outflows or reductions in the pumping from the Delta to the Central Valley and southern California to protect native fish and habitat. Water shortages to agriculture from CALVIN under five hydrologic scenarios serve as a resource constraint for the agricultural model. There are six hydrologic scenarios considered. First is historical hydrology at 2050 levels of development. Secondly, four RCP8.5 climate change scenarios were selected following the guidelines of Fourth California Climate Assessment lead. The four RCP8.5 scenarios are: CanESM2, CRNRMCM5, HadGEM2-ES, MIROC5. Lastly, an additional dry scenario considering a 30% reduction in rim inflows statewide (30PCT) is considered. This last scenario is similar in nature to the one employed in Medellín-Azuara et al. (2008) and in Connell et al. (2012). Hydrologic scenarios are employed by the CALVIN model to calculate water allocations for cities and agriculture such that scarcity and operation and maintenance costs of the statewide water supply system are minimized.

Water shortages by basin from the CALVIN model are included in Table 2 below for each of the model's agricultural region.

Table 2. CALVIN-estimated annual average water shortages by hydrologic scenario (percent with respect to base water use).

Region	*HIST2050*	*CanESM2*	*CNRMCM5*	*HadGEM2*	*MIROC5*	*30PCT*
Sacramento, Delta and East of Delta	1.50	1.46	1.42	1.64	3.34	24.46
San Joaquin Valley	0.00	-	-	0.03	2.83	16.98
Tulare Lake Basin	1.40	0.13	0.12	1.94	3.57	15.17
Other	0.72	0.72	0.72	0.72	0.72	1.38
Total	*1.05*	*0.57*	*0.55*	*1.29*	*2.88*	*15.70*

2.1.5 Changes in Crop Yields

Effects of climate change are likely to entail shifts in crop yields, which have been studied for over a decade. Crop yields are factored in estimating cropping patterns given their direct relationship with crop revenues. Thus crops with smaller yield reductions and higher net returns might be preferred to crops with yield impacted by climate change and lower net returns. Most literature estimates place yield changes within ±10% of standard values, with some crop groups experiencing positive effects and others negative. Alfalfa may experience improved yields at the cost of quality, whereas pasture and almonds would undergo reduced yields. Sugar beets may see slight increases while cotton sees similar decreases. Some estimates claim moderate overall truck vegetable, onion, and garlic yield decreases; other literature reports substantial lettuce increases and extreme broccoli increases. Tomato growth is likely to see slight yield losses, depending on the fate – fresh versus processing – of the tomatoes. Northern grown rice, which makes up most rice cultivation in California, would see small increases, while southern rice would experience similar decreases in yield. Reduced frost damage is liable to improve northern orange yields slightly, with substantial southern losses arising in avocados and oranges. Yields of vine crops are unlikely to shift greatly; however, reductions in suitable land and fruit quality may lead to effective losses. Appendix B in this report provides detailed information on literature relating to climate effects and assumptions used.

2.2 Dairy and Cattle Models

Climate change raises significant concerns about land and other resource use, productivity, food supply, food prices, and farm income in the United States and globally. Despite the depth and breadth of research on the economics of climate change and agriculture, few studies have focused on impacts on livestock or the economic adaptation of these livestock industries to climate change. This section addresses how climate change may affect forage supply and livestock costs and thereby livestock markets and prices.

About 85% of the livestock revenue in California is from pasture-based or harvested forage-based livestock, mostly cattle and calves (27%) and milk from cows (57%), and includes poultry and minor species (sheep and goats, for example). Beef steers and heifers spend about a year as calves with their mother cows, and then feed on pasture and harvested forage. They spend about six months in a feedlot where about 12% of the feed cost is from alfalfa hay (Anderson and Sumner, 2016; backup data and calculations). For dairy cows, an average of 19% of total feed cost is from harvested forage, which includes alfalfa hay, other hay, and silage (California Department of Food and Agriculture, 2015).

2.2.1 Modeling Feed Supply for Dairies

The production of harvested forage crops is linked closely to the dairy industry in California. As with other animal industries, most of the grain and oilseed feed for milk cows comes from out of state, and those prices are determined by national and global markets. However, both dry roughages (mostly alfalfa hay), and especially wet roughages (mostly corn silage and small grain silage) come from California. Climate change has its main effects on the dairy industry through the availability and prices of alfalfa hay and silage. These effects on prices and avilability leads to close linkages between the effects of climate on allocation of crops and the cost of production of milk in California. Further background information regarding cattle feed production in California may be found in Appendix C.

California Dairy and Climate Change in California

We predict that hay and silage production will continue to decline as water and land shifts to tree nuts and other crops with high revenue per unit of water and land. Much hay continues to be shipped in, but silage consumption falls because it is too costly to haul very far given the low value per unit of weight due to high moisture. Table 3 shows that feed costs are the most important factor in production of milk. Therefore, if climate change raises feed costs because of higher water costs in California or loss of grain yield growth or acreage in the Midwest, then dairy costs will rise. Substantial amounts of California-grown hay is also exported to Asia for the dairy industry there and so California dairies must compete for feed in the global market.

Table 3. California Dairy Farm Cost of Production.

	Feed Costs	Hired Labor	Replace Costs	Operating Costs	Marketing Costs	Total cost
	Dollars per CWT					
2006	6.84	1.53	1.98	2.66	0.50	12.64
2012	11.48	1.52	1.24	2.80	0.54	17.57
2013	11.46	1.52	1.08	2.77	0.55	17.37
2014	11.05	1.56	1.37	2.88	0.56	17.42
2015	10.46	1.70	2.12	2.93	0.56	17.78
2016	9.22	1.74	2.10	2.92	0.55	16.53

Source: California Department of Food and Agriculture, Dairy Division

Export markets for milk products also remain vital; competitive prices, especially for non-fat products, allow California to supply for growing demand in Asia. The shift of milk utilization away from beverage milk (from 23.5% in 1996 to 13% just two decades later) means the California industry is more connected to global prices and competition. It follows that small cost increases that exceed cost increases in other places are particularly detrimental for local dairy production.

Table 4. Use of California Milk by Product

	1996	2016
	Percent	
Class 1 (Fluid)	23.5	13.0
Class 2 (Soft, Cultured)	5.2	5.4
Class 3 (Frozen Products)	5.6	2.9
Class 4A (Butter and Dry Milk)	29.4	32.3
Class 4B (Cheese and Whey)	36.3	46.4

Source: California Department of Food and Agriculture Dairy Division

Competition with other U.S. states is more challenging as they have improved productivity and lowered costs, but California remains the largest milk producing state as it loses share to

Wisconsin and other states. California faces higher labor and regulatory costs (for farms and processors) and relatively low milk prices (as a state that ships out generic milk products).

2.2.2 California Milk in the Context of National and Global Markets

Milk produced in California is chiefly exported to other states or countries, with only approximately 20% of dairy goods consumed locally, allowing high demand elasticity in such products. Perishable goods such as fresh milk are generally used locally while storable goods like butter or whey are exported to foreign markets. Production schemes stretch across the Eastern, Midwestern, and Western states of the U.S., including California, New Mexico, Idaho, Wisconsin, and New York, among others; thus, dispersion is a key factor in the dairy market condition. Marketing cooperatives own significant portions of United States dairy production and play large roles in the optimization of production and sale of products. Growth in dairy production has been supported by substantial labor productivity increases and trends towards more consolidated farms. Further information on the marketing of California dairy products as well as production trends is located in Appendix D.

2.2.3 Modeling Impacts on Dairy Under Climate Change

Long-term prospects point towards higher average water costs for dairy feed crop production under climate change. First, climate change is likely to increase irrigation water scarcity and price in the San Joaquin Valley. Climate trends toward higher growing-season temperatures raise the demand for irrigation, while higher winter temperatures reduce snowpack available for irrigation supply. Less surface water available for irrigation reduces groundwater recharge and raises subsequent costs of groundwater access. Second, there are other causes from the changing socio-economic scenarios, which may drive up the water prices. Population growth in California and shifts toward water intensive crops raise water scarcity. Regulations also shift irrigation cost.

More demand for environmental uses have been the most prominent of the regulation-driven impacts. Recently discussed limits on groundwater pumping may further reduce availability of irrigation water. Tradability of water rights raises explicit costs of water in some districts while lowering the water price elsewhere. This section studies the impact of increasing water cost in harvested forage production, particularly alfalfa and corn silage, on dairy cattle and the downstream dairy product. The multistage productions involve forage crops (hay and silage), dairy cattle, milk, and cheese. We could have extended the multistage production to non-fat dry milk and butter, which uses both milk fat and milk solids other than fat. We extended the multistage production to cheese because most dairy products, including butter, milk powder, cheese, and whey are shipped out of California into national and global markets. The demand for dairy product produced using milk from California dairy cows will influence the upstream dairy cows and harvested forage production in equilibrium. The vertical market for cheese production includes markets for water, forage crops, raw milk, and cheese.

Multistage production includes the production of forage crops, milk, and cheese. We assume a single final product in partial equilibrium, where each stage has two inputs used in fixed proportion. We include a realistic numerical illustration to show the potential impacts of higher water costs on the California dairy sector. In the model, two forage crops are fed to the dairy cows in the San Joaquin Valley, wet roughage (mostly corn silage) and dry roughage (mostly alfalfa hay). Alfalfa and silage face different water prices and non-water input costs because the silage market is very local due to the high transport costs that cause them to be cultivated very near to dairy farms. Hay is grown both in the San Joaquin Valley and transported in from other places. We assume both crops have two input fixed proportion production functions using water and non-water inputs. Appendix E contains detailed modeling assumptions and equations employed in the multistage modeling simulation of interest.

2.3 Modeling California Rangeland as a Source of Forage for Beef Cattle

2.3.1 Rangeland Definition

In this study, “rangeland” is defined as any nonforest lands capable of supporting grazing cattle through provision of herbaceous and shrub vegetation species, and includes desert lands fitting this categorization. The potential of these lands to provide sufficient grazing forage is dependent on a number of factors, including climate characteristics. Notably, the definition given here does not exclude public lands used for cattle grazing, unlike the U.S. Census of Agriculture pastureland category. About 92% of all cattle grazing forage in California occurs on private rangeland, while the remaining percentage takes place on public lands, primarily managed by U.S. Forest Service and the Bureau of Land Management (BLM). California consists of a total of about 101 million acres of land, of which 56 million acres are classified as rangeland, although much of that provides very little forage.

In Figure 5-A and Figure 5-B, the rangeland areas are aggregated into 19 Major Land Resource Areas (MLRAs) (USDA-NRCS, 2006). Rangeland areas located in each land resource area share similar climate, soils, and land use activities. California rangeland is dispersed across many MLRAs. However, the Mojave Desert Basin alone accounts for about one third of all rangeland area (but only a small share of forage) in California. Information further defining rangelands and statistics relating to California grazing, such as further land characterizations, are discussed in Appendix F. Note that the Major Land Resource Areas used in the rangeland analysis are different from regions used in the SWAP agricultural production model.

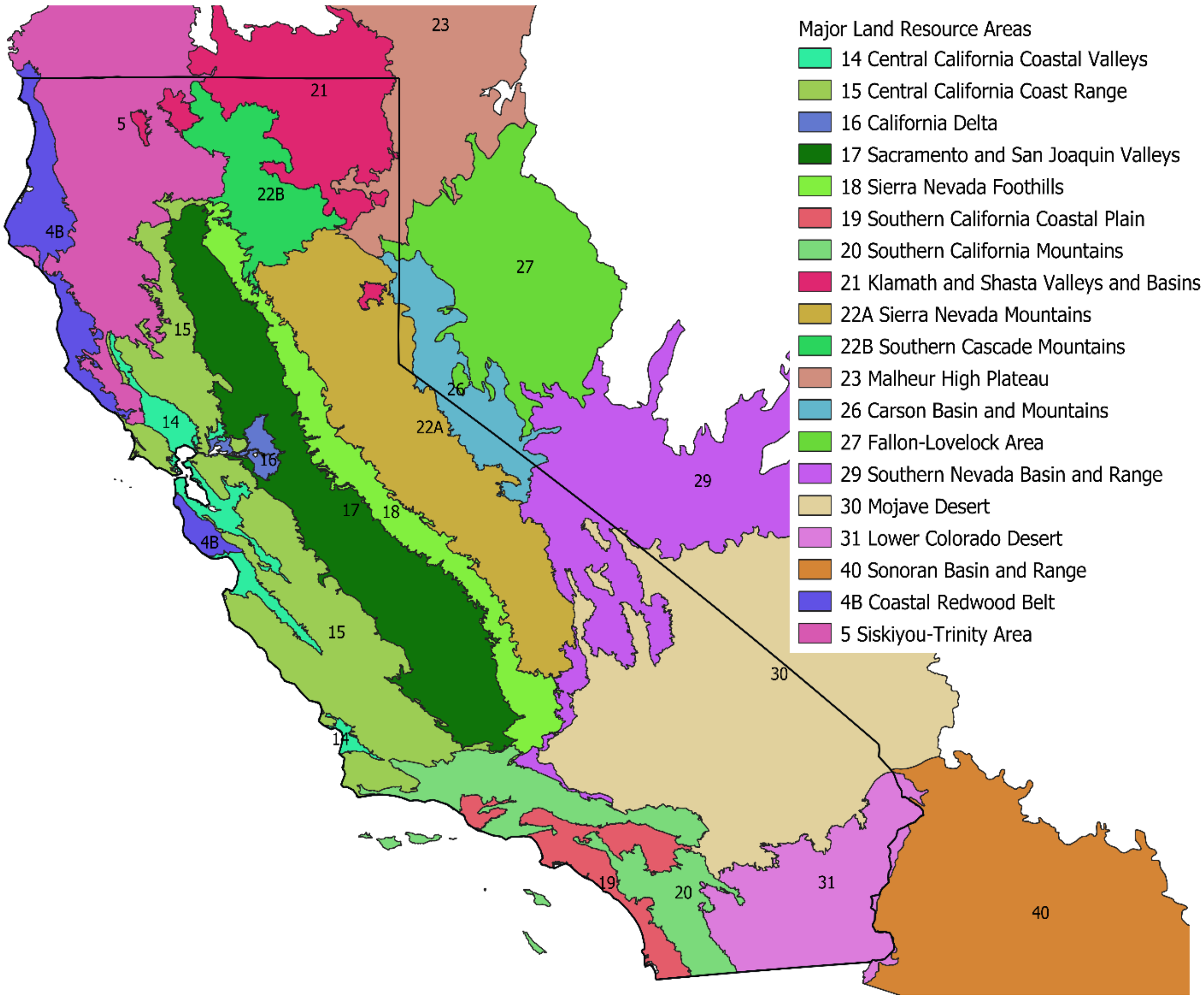


Figure 5-A. Spatial extent of each Major Land Resource Areas for rangeland analysis.

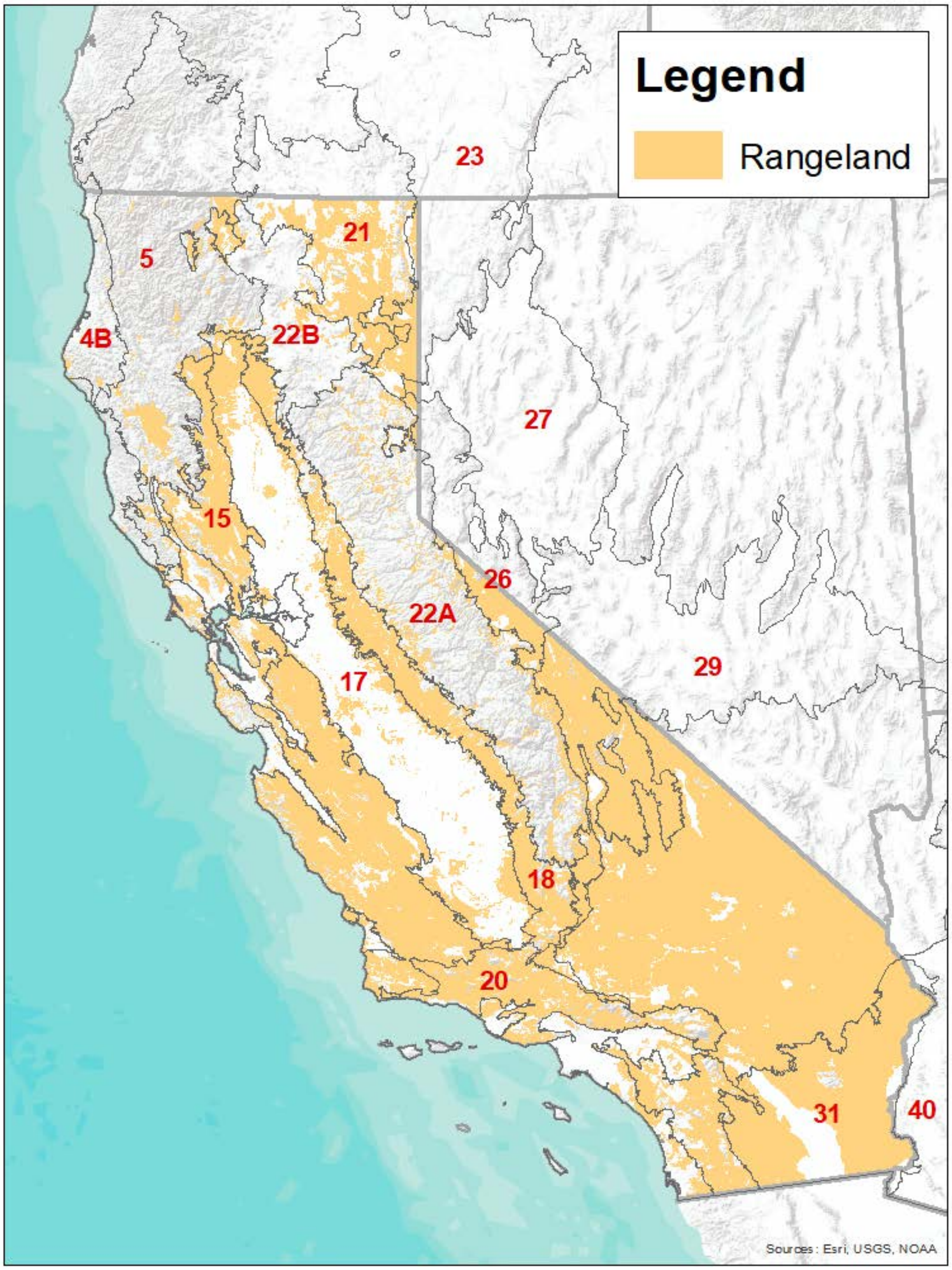


Figure 5-B. Rangeland Areas in Major Land Resource Areas.

2.3.2 Cattle Relevant Rangeland Regions

In Figure 6, the spatial distribution of beef cattle by MLRA was constructed using 2012 Census of Agriculture and January 2012 National Agricultural Statistics Service (NASS) survey data by county (Figure 5). Rangeland was categorized as either federally administered – Forest Service or BLM – or other land owned publicly or privately by using California Protected Area Database information. Following this, rangeland acreage was weighted according to forage consumption by region and type. Data on counties missing from the 2012 Census of Agriculture was grafted from 2012 NASS cattle surveys after calibrating inventories with operation size data. In Figure 6, the greatest portion of beef cattle grazes on land in the Central California Coastal Range (32%), followed by the Sierra Nevada Foothills (19%). While the Central Coastal Range is primarily grazed year-round, other regions experience shifts in cattle numbers, namely towards higher-elevation regions in summer. The Figure 6 share of beef cow inventories by region and seasonality effects on beef cattle share are described in greater depth in Appendix F.

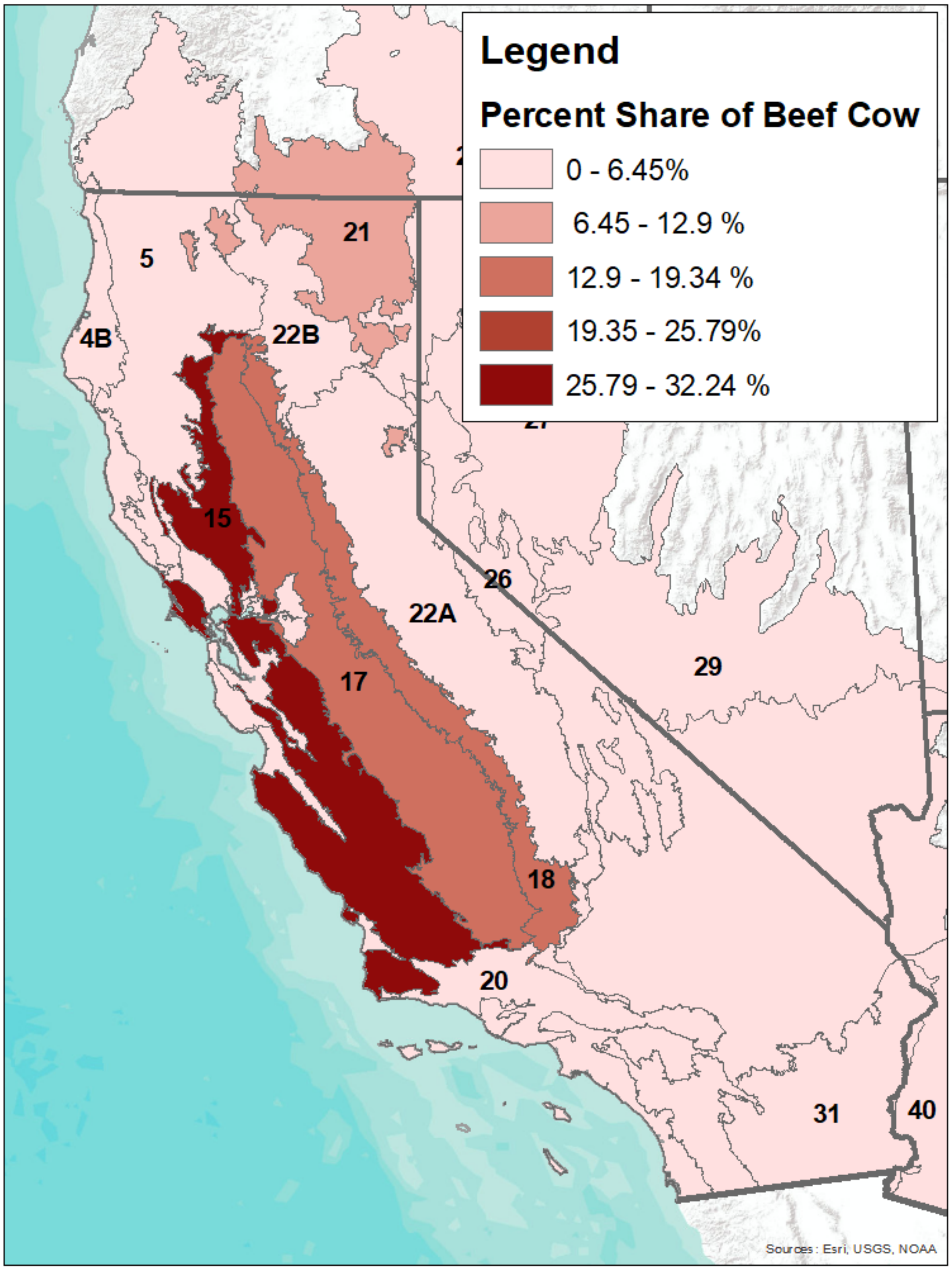


Figure 6. Share of beef cows among Major Land Resource Areas.

2.4 Modeling Pasture Availability under Historical Climate Conditions

2.4.1 Historical Rangeland Climate

Precipitation and temperature both play a role in forage productivity and snow-cover days on rangeland. In this section, we summarize the climate on rangeland, including precipitation and average temperature in January and July. Most precipitation occurs in the winter on rangeland. However, based on the trend analysis in showed in Appendix Table **G-10,** annual precipitation has decreased between 1920 and 2016. Precipitation for MLRA's were found by calculating accumulated daily precipitation data for January and July for 13,660 rangeland regions and finding the acreage-weighted average precipitation for each MLRA. Similarly, in this same time period, average January temperatures have also showed consistent increases in MLRA's, barring high-elevation regions such as the Sierra Nevada Mountains. Monthly averages for January and July temperatures were found using daily averages and subsequently weighting by acre for each MLRA region. The trend estimates are based on acreage-weighted pooled-OLS (Ordinary Least Squares) regressions. Detailed information on precipitation and temperature trends by rangeland area is offered in Appendix G.

2.4.2 Historical Pasture Availability

In the following, we estimated the baseline for pasture availability in California, using the rangeland acreage with snow, days with snow, and pasture greenness. The baseline is based on historical panel data across locations of rangeland area identified using the vegetation habitats listed in Table F-2 of Appendix F. The snow cover data are a simulation output from Variable Infiltration Capacity (VIC) hydrological model using historical weather from 1920 to 2016 (Mao, Nijssen, and Lettenmaier, 2015; Xiao, Nijssen, and Lettenmaier, 2016). The variations and trends of snow cover on rangeland areas from the VIC output are driven only by climatic factors. Mote et al. (2005) showed the variation and trend from VIC output highly agree with historical observations.

To compute the rangeland area with snow for each MLRA, we added up the rangeland area with snow for every year from 1920 to 2016 and computed an average over the years. The rangeland area with more than 30 days of snow is historical average of total the rangeland area which has more than 30 days of snow per year. To compute the rangeland area with average 30 or more days of snow per year, we calculated the annual average days with snow for all rangeland areas (13,660 areas), then selected the areas with more than 30 days of snow and added up the rangeland selected for each MLRA (Figure 7). The trend estimates of area with snow are results based on linear regression estimated separately for each MLRA. The state level trend is computed in two ways: 1) average weighted by cow inventories listed in Table F-5 of Appendix F, and average weighted by acreage listed in Table F-3 of Appendix F.

In addition to the study of rangeland acreage change with snow cover, we analyzed the days of snow cover on rangeland. We grouped the rangeland areas into two categories: light snow areas, which are areas covered by snow but for at most 30 days, and heavy snow areas, which are areas with snow for more than 30 days. The snow days for each MLRA are acreage-weighted snow days over rangeland areas. State level estimates are weighted in two ways: 1) by cow numbers located in each region in Table F-5 of Appendix F, and 2) by acreage listed in Table F-3 of Appendix F. The trend estimates are based on acreage-weighted pooled-OLS regression for all rangeland areas located in each MLRA.

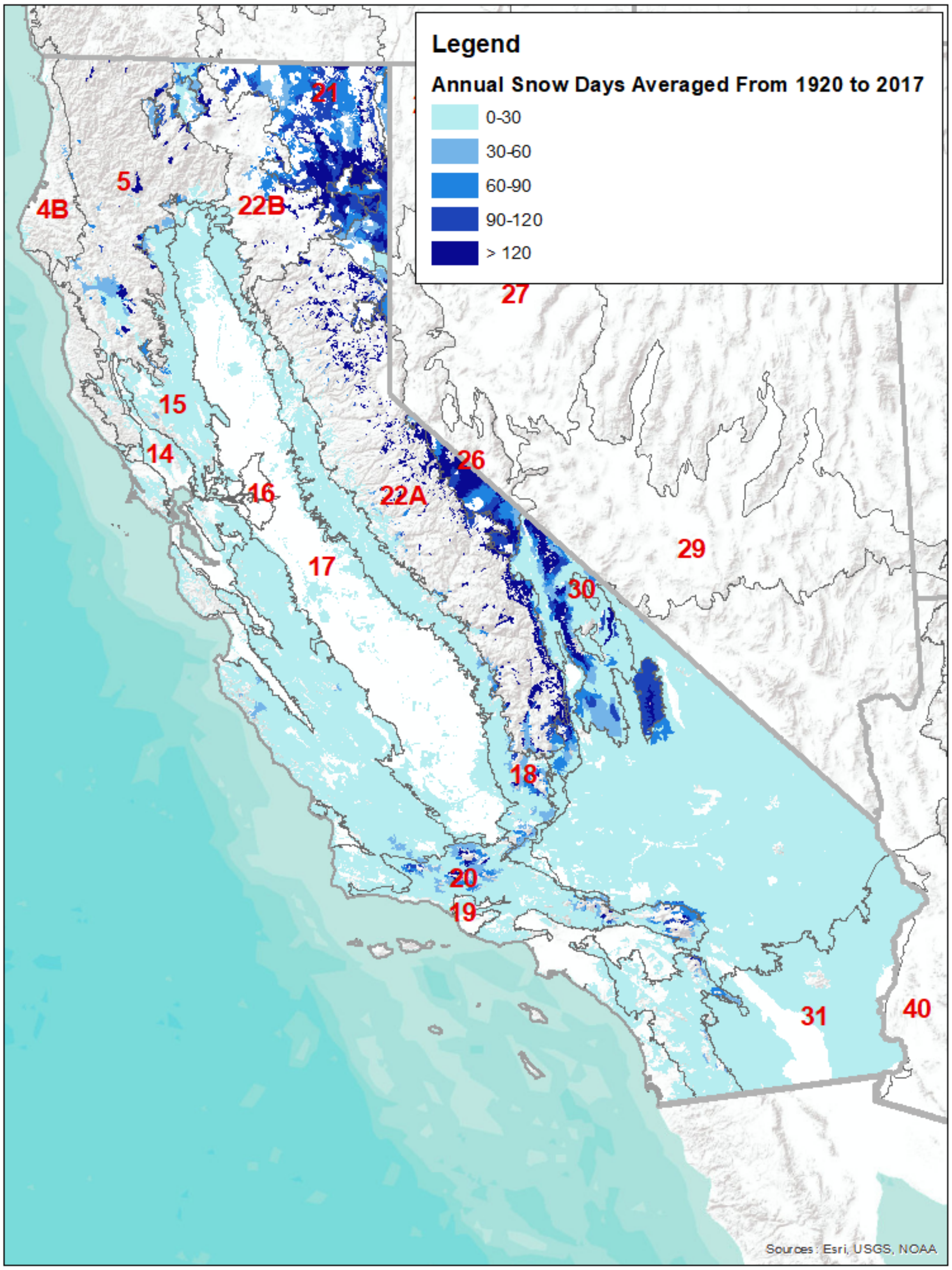


Figure 7. Coverage of average annual snow days in California from 1920 to 2016 with lighter (dark) blue shades indicating lower (higher) annual snow days.

2.4.3 Greenness

The Normalized Difference Vegetation Index (NVDI) was used to estimate greenness trends for 1982-2016. Composite 32-day imaging collected from Google Earth Engine and Landsat images were used to find maximum fall and spring NVDI values. The NVDI by MLRA was then found by average acreage-weighted maximums from fall and spring and averaging over the annual cycle. State averages were also computed weighting by both cow inventory and rangeland acreage. We reported the trend as percentage change of baseline

of NDVI using pooled-OLS,

The percentage change is the acreage-weighted average of percentage change in max NDVI values across MLRAs per year.

Detailed information regarding greenness estimation can be found in Appendix G.

2.4.4 Projected Pasture Availability

We estimated the trends in acreage of rangeland with snow and days with snow on rangeland from 2010 to 2050 under four climate models, CanESM2, CNRM-CM5, HadGEM2-ES, and MIROC5. The data are based on the output from Variable Infiltration Capacity (VIC) model forced by LOCA downscaled climate projections from Scripps Institution of Oceanography (Pierce et al., 2014). The estimates were divided by the baseline rangeland acreage with snow and days with snow from 1920 to 2016. For each model, we calculated the state level average as a weighted average of the percentage change across MLRAs.

2.4.5 Pasture Availability from Rangeland Covered by Snow

Climate change may alter California rangeland conditions and the grazing patterns of the cattle herds they support. Changing temperatures and precipitation patterns may influence the type, mix, and productivity of rangeland vegetation species (Hatfield et al., 2011). In addition, warming temperatures and changing snowfall amounts and seasonality will reduce areas covered by snow, especially in areas with milder climates (Mote et al., 2005). Studies show the average number of days that areas are covered by snow and the average snowpack size declines under climate change conditions (Hamlet et al., 2005; Lemke et al., 2007). These changes imply that there may be more rangeland acreage available for grazing and cattle may be able to graze on rangeland sometimes covered by snow for longer periods in each year. In response to climate change impacts on pasture vegetation growth and rangeland acreage, ranchers will have an incentive to adjust grazing management, cattle herd size, pasture-hay ratios, and length of grazing periods. In short, climate change significantly affects cattle grazing systems through its influence on pasture vegetation conditions and rangeland availability.

The rangeland area used in this report to estimate pasture supply for beef cattle is defined as land with potential forage available for grazing. The rangeland area is defined using the California Wildlife Habitat Relationships Database (CWHR) (Mayer and Laudenslayer, 1988) and California landcover information from GAP project (US Geological Survey, 2011). The vegetation classifications identified as rangeland include some herbaceous dominated habitats, shrub dominated habitats, and some types of tree dominated habitats.

We model the climate change impact on rangeland to an extent that we could approximate the changes in the amount of actual forage that could be available for grazing in California under climate change. We investigate how snow cover conditions have changed in the past 97 years (from 1920 to 2016) on California rangeland and project how it will change from 2010 to 2050. The preliminary results indicate the pasture availability changes with respect to the overall historical trend of snow cover days. The share of snow-cover days was computed for rangeland

and different vegetation types within rangeland from 1920 to 2016. For example, the annual share of snow-cover days for California rangeland is the aggregated sum of rangeland acreage and the snow-cover days within a year divided by the total acre-days (total rangeland acreage with 365 days). An annual trend is included in the regression for the share of snow-cover days with 97 observations (1920 to 2016).

2.4.6 California Rangeland and the Climate Data

While long-run disaggregated weather data can be obtained with relative ease, this is not the case for hydrological and pastureland data. Detailed hydrological data are typically confined to experimental fields in some states. Fine level land use information only became available recently as a result of advanced remote sensing technology. Detailed cattle inventories at pastureland field level are limited to case studies conducted over a short time period. Some feasible alternative data for weather, hydrological conditions, pastureland, and cattle inventory are described in the following section. The analysis relies on model-generated hydrological conditions. The weather data which serve as inputs for hydrological models are selected for consistency purposes.

The historical weather dataset is taken from the University of Washington's Drought Monitoring System for California. The data set is daily precipitation and temperature maxima and minima interpolated at 1/16-degree spatial resolution. The interpolation process was conducted over the West Coast Region, which is based on 2,415 stations over the continental U.S. and part of Canada selected based on their long and continuous records, which were selected based on continuous records of long duration. Of these stations, 102 are located within California. Details about the weather data and interpolation methods are provided in Mao, Nijssen, and Lettenmaier (2015), Xiao, Nijssen, and Lettenmaier (2016), Maurer et al. (2002) and Wood and Lettenmaier (2006). The orographic effects which are important in California are incorporated by calibrating the data set with the long-term (1961–1990), high-resolution, monthly precipitation climatology for the United States obtained from PRISM. Different from the L15 data set, the California weather data is suitable for trend analysis because the interpolation process includes stations with consistent long-run records.

Corresponding simulated hydrological data are provided by Mao, Nijssen, and Lettenmaier (2015). The hydrological data includes snow water equivalent, soil moisture content, sublimation of water vapor from the surface, evaporation, transpiration from plants, runoff, surface heat fluxes, etc. The hydrological data is an output from the Variable Infiltration Capacity (VIC) model (Liang et al., 1994). The VIC model is a hydrologic model that has been successfully used to simulate hydrological conditions in many large basins and regions (Nijssen, Schnur and Lettenmaier, 2001; Mote et al., 2005; Wu et al., 2007). The VIC model uses weather station, wind radiation station, and reanalysis data to generate estimates of hydrological values on a daily basis. The model was implemented with elevation bands that represent variability in land surface processes, which is particularly important to represent topographic effects on precipitation and snow accumulation and melt.

Using the land acreage data from USGS national GAP analysis project (US Geological Survey, 2011) and the habitat classes from California Wildlife Habitat Relationships Database (Mayer and Laudenslayer 1988), the paper identifies the California rangeland as land with potential forage for grazing. The vegetation classifications identified as rangeland include herbaceous dominated habitats, shrub dominated habitats, and some types of tree dominated habitats.

2.4.7 California Pasture Availability Under Climate Scenarios

Following the preliminary result of the trend in share of acre-days for rangeland covered by snow, we project the changes in area and snow cover period for rangeland under various hydrological scenarios, including CanESM2, CNRMCM5, HadGEM2, and MIROC5.

3: Results

In this section we present results from modeling of crops, dairies, and beef cattle by 2050 under historical and various scenarios of climate change and water supply conditions.

3.1 Change in Irrigated Area and Water Use

The modeling results overlay the effects of urbanization, technology, and markets, with the hydrologic scenarios modeled in CALVIN and crop yield response by 2050. Table 5 below shows the predicted percent change in irrigated area by 2050 for each hydrologic scenario. Under historical conditions and for most climate scenarios analyzed, idle land due to shortage or urbanization is roughly 6% statewide for the areas covered by the model. Under the scenario simulating a 30% reduction in rim inflows, idle land reaches nearly 10% of the base amount with the highest relative shortages occurring in the Sacramento Valley (10 %) and the Tulare Lake Basin (13%). Shortages in all other areas, including the coast, are close to 9% for all hydrologic scenarios. Conversion from agriculture to other uses seems to be the dominant effect on irrigated area changes.

Table 5. Changes in irrigated crop area among hydrological scenarios by 2050 with respect to base land use.

	HIST2050	CanESM2	CNRMCM5	HadGEM2	MIROC5	30PCT
Sacramento, Delta/East of Delta	-5.51%	-5.53%	-5.53%	-5.55%	-5.55%	-9.88%
San Joaquin Valley	0.00%	0.00%	0.00%	0.00%	0.00%	-6.57%
Tulare Lake Basin	-8.58%	-8.57%	-8.57%	-8.57%	-8.58%	-12.92%
Other	-8.59%	-9.94%	-9.94%	-9.94%	-9.94%	-10.08%
Total Change in Irrigated Area	-6.12%	-6.37%	-6.37%	-6.37%	-6.37%	-10.39%

Water delivered to agriculture in 2050 for each hydrologic scenario and region is provided in Table 6 below. The change in overall water supply shortage by region ranges from 3.7 to 4.1%, with the historical scenario facing the smallest reduction in water deliveries to agriculture from the CALVIN model (Table 6). These percentage reductions are nearly half of the reductions in total irrigated area by region, suggesting conversion of agriculture to other uses is the dominant effect. For the 30% reduction in rim inflows scenario, the shortage increases to 12.4%. The areas with the highest reductions in water use are the Sacramento Valley, the Delta and east of the Delta agriculture, with 16.3 % with respect to 2010 base water use. The Tulare Lake Basin follows in the magnitude for shortage with respect to base use at 13.5%.

Table 6. Changes in water use by region among hydrological scenarios by 2050 with respect to base water use.

	HIST2050	***CanESM2***	***CNRMCM5***	***HadGEM2***	***MIROC5***	***30PCT***
Sacramento, Delta/East of Delta	-1.91%	-1.91%	-1.92%	-1.97%	-2.35%	-16.31%
San Joaquin Valley	-0.29%	-0.24%	-0.24%	-0.24%	-0.40%	-10.94%
Tulare Lake Basin	-7.51%	-6.95%	-6.95%	-7.00%	-7.26%	-13.48%
Other	-6.52%	-8.03%	-8.03%	-8.03%	-8.02%	-7.91%
Total Change in Applied Water	-4.87%	-4.95%	-4.95%	-4.98%	-5.15%	-12.24%

When the large crop categories are analyzed, field and grain crops are reduced by nearly a quarter of their original value. Feed crops follow, with roughly 11.5% reduction under historical climate and up to 22% under the 30PCT scenario (Table 7). In contrast, increases of roughly 6% in permanent crops could be expected for most scenarios. Vegetables and non-tree fruits change in area is rather modest and we project reductions of roughly 3% for most climate change scenarios.

Table 7. Changes in irrigated crop area by crop category among hydrological scenarios by 2050 with respect to base land use.

	HIST2050	***CanESM2***	***CNRMCM5***	***HadGEM2***	***MIROC5***	***30PCT***
Feed Crops	-12.19%	-8.43%	-8.43%	-8.47%	-8.58%	-22.10%
Field and Grains	-19.49%	-21.87%	-21.87%	-21.84%	-21.75%	-24.57%
Fruit and Nut Trees	5.54%	5.42%	5.42%	5.42%	5.42%	5.26%
Vegetables and Non-Trees Fruits	-0.09%	-3.12%	-3.12%	-3.11%	-3.11%	-3.11%
Total Change in Irrigated Area	-6.12%	-6.37%	-6.37%	-6.37%	-6.37%	-10.39%

The effect of increasing demands on California's specialty crops by 2050 coupled with yield improvements averaging 25% for the mix of crops partially offsets the adverse impacts of reduced irrigated areas, water shortage, and climate-related yield declines. In the worst case scenario (30 PCT), revenue losses are roughly 4.85%. Crop categories with the highest percentage losses with respect to base 2010 conditions are again feed crops, field, and grain. Minor losses could be expected for fruit and nut trees, vegetables, and other fruits. The reduction in feed crops has implications especially for dairy production as discussed below.

Table 8. Changes in gross crop revenues among hydrological scenarios by 2050 with respect to base land use.

	HIST2050	*CanESM2*	*CNRMCM5*	*HadGEM2*	*MIROC5*	*30PCT*
Feed Crops	-13.11%	-9.17%	-9.17%	-9.20%	-9.20%	-16.33%
Field and Grains	-14.14%	-14.75%	-14.75%	-14.74%	-14.72%	-18.57%
Fruit and Nut Trees	-1.53%	-1.29%	-1.29%	-1.29%	-1.30%	-1.33%
Vegetables and Non-Trees Fruits	0.49%	-4.10%	-4.10%	-4.10%	-4.09%	-4.08%
Total Revenue Losses	**-2.50%**	**-4.04%**	**-4.04%**	**-4.04%**	**-4.04%**	**-4.85%**

Overall, despite the climate-related water shortages and yield loss, the agricultural sector remains strong due to the higher demand for California specialty crops, technological improvements, and other factors. Comparing climate change scenarios to historical 2050 conditions (bottom row in Table 8), CanESM2, CNRMCM5, HadGEM2, and MIROC5 cause a decline in gross revenues of roughly 3% with respect to the historical hydrology scenario in 2050. The 30 percent scenario, on the other hand, shows an additional 0.8% in gross revenue losses. Since technological adaptation often has a direct positive effect on crop yields, Medellín-Azuara et al. (2012) provide a sensitivity analysis on this modeling assumption. Overall results of such sensitivity analysis show that estimated cropping patterns and gross revenues for the analyzed scenarios are maintained for a wide range of assumptions on technological adaptation for improved crop yields.

3.2 Dairies

The simulated increase in water cost due to climate change reduces acreage and increases production costs of downstream products, including hay, silage, milk, and cheese. Before the water cost shock, the water represents about 12% of total hay production cost and about 16% of total silage production costs. Hay represents about 17% and silage about 19% of average milk production costs. The cost share of milk in cheese production is about 86.5%. When water cost doubles, the water cost share rises to 21% in hay production and 28% in silage production. As a consequence, the hay cost share in milk production rises to 18%, the silage cost share rises to 20% and the cost share of milk in cheese rises to 87%. For simplicity, these calculations assume that the prices and usage of other inputs involved in the multistage production remains constant.

Table 9 shows the changes in prices and quantities for relevant product with assumed irrigation water cost shock (a doubling of cost of water for each crop). The higher cost of water implies a higher cost of alfalfa hay by 12% and a higher cost of silage by about 16%. As a result of these feed cost increases, the price of milk from the farm increases and the price of cheese increases by 4.3%.

Table 9. Estimated impact of high water price on roughage, milk and cheese productions in California.

Estimates	Unit	Before water price change	After water price change
Water price for hay/silage	$/m^3$	0.04/0.08	0.08/0.16
Hay price	$/metric ton	262	293
Silage price	$/metric ton	80	93
Milk price	$/kg	0.34	0.35
Cheese price	$/kg	3.81	3.98
Cheese Price %	-	-	4
Cheese Quantity %	-	-	-22

Source: Author calculations.

The challenge for the California dairy industry is that the price elasticity of demand for California cheese is very elastic. We assume an elasticity value of -5, indicating that for every percentage point increase in price, demand decreases by five percent points. The rationale is that California-produced dairy products are sold in world markets where the California share is very small. The implication is that the quantity demanded of California cheese falls by 22% in the long run. A similar result would follow from a similar simulation of the use of milk in non-fat dry milk (or skim milk powder) and butter. The cheese and the butter/powder use comprise about 80% of California milk produced. Hence a substantial irrigation water increase is likely to reduce competitiveness of the California dairy industry, which faces a highly elastic demand function.

3.3 Cattle

3.3.1 Impacts of Climate Change in California Rangeland on the Cattle Grazing Industry

There are about 56 million acres of rangeland in California. The rangeland area is defined using the California Wildlife Habitat Relationships Database (CWHR) (Mayer and Laudenslayer, 1988). The top four vegetation types by area on rangeland with potential forage is desert scrub (33%), annual grassland (13%), alkali desert scrub (7%), and Blue Oak-Foothill Pine (7%). More information on rangeland vegetation types can be found in Appendix F.

About 21 million acres of rangeland is privately owned, which constitutes about 38% of total rangeland with potential forage for grazing. Private agents own about 6 million annual acres of grassland, which is about 83% of all the annual grassland in California. US Forest Service and Bureau of Land Management owns about another 38% of total rangeland. The top four vegetation types by area of the rangeland owned by USFS and BLM are desert scrub (40%), sagebrush (10%), mixed chaparral (9%), and alkali desert scrub (7%). More information on rangeland ownership can be found in Appendix F.

3.3.2 Grazing and Forage Consumption on Private Pastureland

We find the pasture production on privately owned rangeland is most relevant to beef cattle production. By assuming the average beef cow is 1,300 pounds, the 600,000 beef cows (U.S. Census of Agriculture, 2012) require 9,360,000 AUMs (average 1.3 AUMs per cow, 600,000 beef cows for 12 month). Based on the pasture-hay ratio, about 292,500 AUMs consumed by beef cows are from hay (3.1%), and the rest are from pasture.

Forage grazed on other public programs are small comparing to grazing activities on lands controlled by USFS and BLM (United States Government Accountability Office, 2005). We estimated that beef cows raised in California consume about 479,974 AUMs from grazing lands authorized by USFS and BLM (5.1%), and 8,602,525 AUMs from pasture from private pastureland (91.9%).

In the next section, we will quantify the impact of snow cover on rangeland acreage in terms of impacts on accessible forage production by cattle. The accessible forage dry matter by cattle depends on the plant type, the soil of the location, the slope, and the weather. We simulate how pasture acreage and quantity available for grazing change under different hydrological climate change scenarios, including CanESM2, CNRMCM5, HadGEM2, and MIROC5.

Baseline

About 51.1% of California's total effective rangeland forage was historically covered by any snow each year from 1920 to 2016, weighted by cow inventories. About 21.5% of total California rangeland was covered by snow for more than 30 days per year. The area with average snow cover days greater than 30 days is about 21.8% of the total effective rangeland. This area is mostly mountain rangeland, including Klamath and Shasta Valley and Basins (92.8% of the rangeland has more than 30 days of snow cover), Sierra Nevada Mountains (76.2%), Southern

Cascade Mountains (80.4%), Malheur High Plateau (89.8%), Carson Basin and Mountains (95.9%), and Siskiyou-Trinity Area (50.2%). Figure 8 shows the spatial extent of the share of the effective rangeland area covered by snow for more than 30 days in each Major Land Resource Area. The Appendix Table G-1 lists the region-specific acreage of area with more than 30 days of snow cover in California.

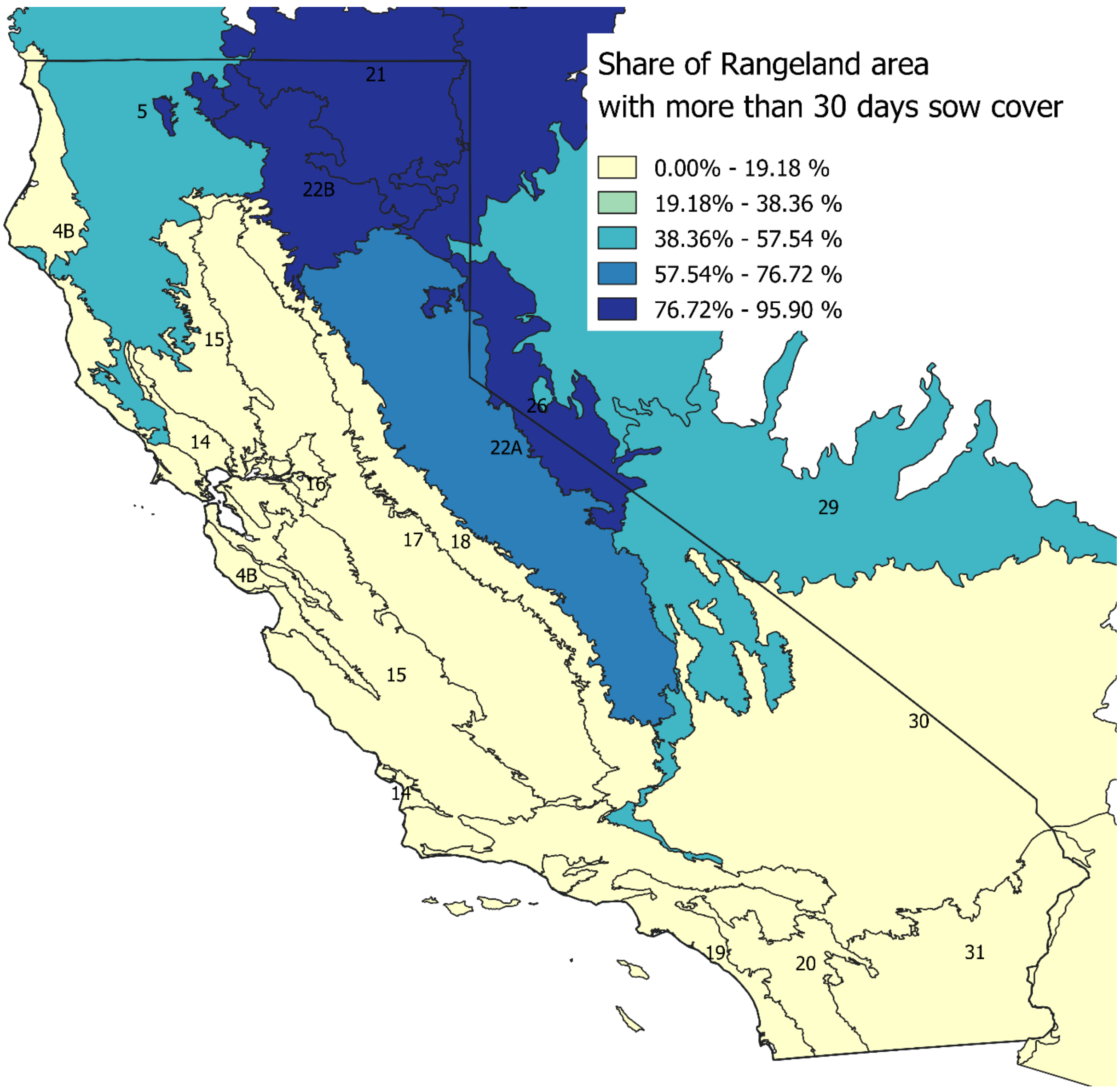


Figure 8. Spatial extent of shares of rangeland area with more than 30 days of snow cover averaged over 97 years.

Trends show that from 1920 to 2016, California rangeland has 0.082% less area each year with any snow cover in a year and 0.033% less area each year with snow cover for more than 30 days in a year. Appendix Tables G-1 and G-2 show the baseline acreage and share of rangeland area affected by snow across Major Land Resource Areas in California. Appendix Table G-3 shows the estimated annual trends in rangeland acreage covered by snow across different Major Land Resource Areas.

Days with Snow Cover

On average, California rangelands have about 24 snow cover days per year from 1920 to 2016, weighted by the number of beef cows in each region. Regions such as Sierra Nevada Mountains, Southern Cascade Mountains, and Carson Basin and Mountains have large variation in snow cover days across rangeland areas, ranging from four to 28 days in light snow area, and 55 to 122 days in heavy snow area. The rangeland areas across California are having gradually fewer snow cover days from 1920 to 2016. Areas with heavy snow are seeing 0.28% decrease in snow cover days while areas with light snow are seeing 0.98% decrease in days with snow at state level, with an average of 0.81%. The decrease in the number of days is larger for heavy snow areas. In the past 97 years, the trend showed that on average there were 0.98% less snow cover days in heavy snow areas, and 0.81% less snow cover days in light snow area at state level. The trend indicates that the snowlines on rangeland were moving up in the past 97 years, and there were more areas each year with no snow cover from 1920 to 2016.

Appendix Table G-4 shows the baseline average days of rangeland with snow across MLRAs in California from 1920 to 2016. Table G-5 shows the trend of days on rangeland with snow across MLRAs from 1920 to 2016.

Baseline California Rangeland Greenness

The rangeland in California is greener over time from 1982 to 2016, with 0.17% increase in spring max NDVI, and 0.20% increase in fall max NDVI. In general, rangeland is greener in spring, with larger NDVIs than in fall. Areas with high precipitation, such as Central California Coastal Range, have greener rangeland than areas with low precipitation, such as Mojave Desert Basin and Range. Areas with large forest canopy, such as Coastal Redwood Belt, also had large NDVI values for both spring and fall. Appendix Table G-6 shows the spring and fall max NDVI from 1982 to 2016 across MLRAs.

Rangelands are getting greener in spring and fall across all MLRAs, other than California Delta, Southern California Mountains, and Lower Colorado Desert. These three regions fed about 3% of the beef cows in California in 2012. Appendix Table G-7 shows the trends in max NDVI during spring and fall across Major Land Resource Areas.

Projected Forage Availability from 2010 to 2050

We find that the total rangeland availability will increase by 1.14% by 2050, with less acreage with snow and fewer snow days. We use the changes in acreage-days of rangeland to approximate the changes in forage availability for beef cow grazing, assuming most rangeland stays viable from 2010 to 2050. The total area covered by snow in California on average falls by 5.74% by 2050 compared to 2010. The total rangeland acreage with snow for more than 30 days per year in California falls by 3.56% by 2050. Table 10 shows the state level weighted average of rangeland area with snow. The days with snow on all rangeland in California is projected to decrease by 20% by 2050. The days with snow on rangeland ever with snow but at most 30 days is projected to decrease by 17.2% by 2050. The days with snow on rangeland with snow for more than 30 days will decrease by 23.6%. Table 11 shows the state level weighted average of days with snow on rangeland in California.

Table 10: Percentage changes in acreage of rangeland in California by 2050 by hydrologic scenarios (percent with respect to historical average).

Rangeland	CanESM2	CNRM-CM5	HadGEM2	MIROC5	Ave.
Rangeland with Snow	-5.18%	-1.49%	-6.70%	0.72%	-5.74%
Rangeland with more than 30 Days of snow	-4.29%	-1.17%	-3.12%	-1.45%	-3.56%

Notes:

(1) The average column is the weighted average of percentage change in acreage with now across MLRAs. The values in the average column are not a simple average from the values displayed under the four climate scenarios.
(2) To calculate the state-level changes, the regional changes in rangeland area with snow cover are weighted by the share of beef cow and the share of rangeland area with snow cover.

Sources: Calculation based on the snowpack projections generated through use of Variable Infiltration Capacity (VIC) model forced by LOCA downscaled climate projections from Scripps Institution of Oceanography (Pierce et al., 2014), and rangeland polygons from National Gap Analysis Project (GAP), National Geospatial Data Asset (NGDA), USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)

Table 11: Percentage Change in days with snow on rangeland in California by 2050 by hydrologic scenarios (percent with respect to historical average).

Rangeland	CanESM2	CNRM-CM5	HadGEM2	MIROC5	Ave.
All Rangeland in California	-38.4%	-3.6%	5.2%	-14.4%	-20.0%
Rangeland with Snow for at Most 30 Days	-23.6%	-8.8%	-8.4%	0.0%	-17.2%
Rangeland with Snow for More Than 30 Days	-36.4%	-8.4%	-28.8%	-16.8%	-23.6%

Notes:

(1) The average column is the state level weighted average of percentage change in acreage with now across MLRAs.
(2) The values in the average column are not the average from the four climate scenarios.

Sources: Calculation based on the snowpack projections generated through use of Variable Infiltration Capacity (VIC) model forced by LOCA downscaled climate projections from Scripps Institution of Oceanography (Pierce et al., 2014), and rangeland polygons from National Gap Analysis Project (GAP), National Geospatial Data Asset (NGDA), USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)

With the increase in forage supply, the rangeland could feed 1.14% more beef cows in California, about 6.6 thousand more beef cows in California by 2050. Appendix Table G-8 and Table G-9 show the changes in rangeland acreage and snow days by MLRAs by 2050.

4: Discussion

4.1 Crop Farming

This research shows that climate change may pose some challenges to crop farming in California due to potential yield losses in various crop categories and more frequent and intense droughts causing water shortages to agriculture. Modeling results from CALVIN for the set of climate scenarios in this study indicate that water shortages may turn out to be modest to agriculture even in drought events, due to the water supply system interconnectivity and the existence of groundwater reserves that can buffer large water shortages like in recent droughts (Medellín-Azuara et al. 2015). A successful implementation of the 2014 Sustainable Groundwater Management Act (SGMA) requiring groundwater basins statewide to achieve sustainability will improve the prospects for making groundwater reserves available. However, reducing groundwater use may entail permanent fallowing of currently irrigated areas in highly overdrafted basins in the San Joaquin Valley and other areas. Impacts of these permanent land fallowing will likely be larger than water shortages and climate-related crop yield losses. Change in irrigation requirements remains an area of further research since evidence from current research remains mixed.

Agricultural land use coverage is expected to decline by 2050 according to projections using the LUCAS model. Similarly, Thorne et al. (2017) suggest more climate vulnerable agricultural land in the Central Valley may convert to non-agricultural land including urban footprint expansion. Other factors in addition to SGMA implementation include soil salinization due to poor drainage and potential future regulations limiting nitrate loads and air emissions. Yet highly innovative agriculture in California has demonstrated its ability to adapt to environmental, economic, and regulatory conditions with remarkable success.

Potential impacts of climate change on crops are broadly consistent with previous studies (Medellín-Azuara et al. 2012) in that water shortages might be higher in the Central Valley, posing challenges to maintain feed, field, and grain crops. Nevertheless, feed crops support dairy and beef cattle which contribute 25% of the agricultural value in the state; hence, tradeoffs exist between some feed crops and permanent crops. Agriculture in the coastal areas is often reserved to higher value specialty crops, since highly populated areas in the coast drive higher opportunity costs on water. Pressure to agricultural areas in the coast not only comes from competing water uses but also from urbanization. In the South Coast, reductions in irrigated area can be around 22% due to urbanization and potential water trades with cities regardless of the climate scenario.

In sum, impacts of climate change to crops will cause some non-trivial reductions in irrigated area which may range from 6.4% to 10.4% of current conditions. Highest impacts may occur in the Central Valley on feed, grain, and field crops. Higher irrigation requirements in crops may cause some additional water scarcity. Yet the effects of groundwater regulations, urbanization, and technological adaptation by the time horizon in which climate changes occur may have a dominant effect on crop farming over climate change.

4.2 Dairies and Cattle

The modeling of water cost in dairy cattle feed production under climate change highlights the vulnerability to irrigation water increases that San Joaquin Valley farm industries face when elastic demands for processed products to which they contribute are included. We used fixed proportion frameworks to link water costs to farm outputs and farm outputs to processed products. The model is consistent with work done in the California context using the CVPM model (Central Valley Production Model). That model has the tradeoff curve between irrigation efficiency and the irrigation capital cost. Both models imply that the more farms can use capital and innovations to substitute away from costlier water, the more these major impacts can be moderated. For example, if higher water costs cause more subsurface drip irrigation use to reduce water per ton of alfalfa hay, the less the impact on the price of hay and the resultant price of milk and cheese.

This report does not discuss in detail the full impact of climate and climate change on beef cattle in feedlots. Some research has found climate may influence beef cattle weight gain efficiency in feedlot. Heat stress may decrease cattle efficiencies of gain in feedlots that lack air circulation (Mader, 2003). Climate change may also influence corn and oilseed production, which are the predominant feeds in feedlots. This report investigates the impact of climate change on pasture productivity and grazing cattle. The impact of climate change on cattle in feedlots is a future research topic.

Irrigation may affect the mountain pasture under climate change. According to the U.S. Census of Agriculture, of the 14.4 million acres of private pastureland, 3% were irrigated in 2012. Siskiyou has the most irrigated pastureland, with 56 thousand acres of irrigated pastureland. Four other counties with large areas of irrigated pastureland are Solano (33 thousand acres), Lassen (31 thousand acres), Modoc (28 thousand acres), and San Joaquin (24 thousand acres). These five counties constitute about 38% of total irrigated pastureland in California.

Various non-climate factors also influence areas for grazing. These may include changes in vegetation canopy and changes in land use around and on the site. Mote et al. (2005) shows the non-climate factors play minimal role in the variation and trend of snow pack sizes. Non-climate factors may also cause rangeland to be no longer practical for grazing. For example, the increase in rangeland area due to less snow may not be feasible for grazing when it is too costly to install fence and provide a water source to cattle on the rangeland. It is important to understand that the trends estimated does not incorporate non-climate driven factors.

Many studies have found that NDVI is highly correlated with above-ground plant production (ANPP) (Piao et al., 2006; Paruelo et al, 1997; Prince, 1991). Prince (1991) found there exists strong linear relationship between Sahelian herbaceous grass net production and seasonal summed NDVI calculated for the same location. Paruelo et al (1997) found a positive and statistically significant relationship between annually integrated NDVI and annual net primary production for grassland area in Central Grassland Region with low human impact. In this report, we did not investigate NDVI as a proxy for forage production.

For the forage availability projections, we assumed most rangeland stays viable from 2010 to 2050, which may underestimate the increase in forage availability in the snow area. While the Southern California Coastal Plain and Mountains and Lower Colorado Desert had decreasing NDVIs, most rangeland is getting greener in the spring and fall, especially in the snow area from 1982 to 2016. If assuming the current trends in spring NDVI on rangeland in California continus from 2016 to 2050, the rangeland on average will be 6.8% greener in spring by 2050. Research found links between seasonal sum of NDVI and annual aboveground net primary production (Piao et al., 2006; Paruelo et al, 1997; Prince, 1991) and annual grass primary production (Hunt and Miyake, 2006). However, the trend in the annual integrated NDVI may be much smaller than the 6.8% due to hydrological constraints during the summer (Thorne et al, 2015). We consider the 1.14% increase in forage availability as a lower bound of the increase in rangeland productivity under the assumption that most rangeland remains viable from 2010 to 2050.

We did not report the standard errors for our trend estimates. We also assumed the rangeland areas within each MLRA are independent from each other, which may not be true due to spatial correlations. Estimates could be improved by constructing a spatially weighted matrix using distances and elevations differences between rangeland areas.

4.3 Adaptation

Agronomic and environmental constraints to agricultural production will be exacerbated by climate warming. Direct impacts, such as a reduction in winter chill hours and extreme heat waves, coupled with indirect impacts, such as greater prevalence of crop pests and water scarcity, will limit agricultural suitability (Pathak et al., 2018). Climate change adaptations for chill hours include the implementation of future projections to allow farmers to select their crops accordingly, breed for low-chill hour requiring cultivars (Luedeling, 2012; Guerriero et al., 2010), artificially inducing tree dormancy (Luedeling, 2012), microclimate manipulation (Campoy et al., 2011), using overhead irrigation to affect chill accumulation (Erez, 1995), and using chemicals to break dormancy and promote homogeneous fruit (Dozier et al., 1990; Erez et al., 2008). A combination of different pollinator species, habitat augmentation, and management practices is beneficial for promoting reliable and economical pollination of crops. Changes in agricultural practices in response to changing water supply include improvements in irrigation efficiency adoption of new technology and shifts in cropping pattern toward less water intensive and higher value crops.

Adapting to climate warming in the crop, dairy and beef sectors will require increased human intervention, improved technologies, and ultimately financial investments to maintain agricultural productivity. Some models suggest that farms may move to more diversified operations as an adaptation to drier and hotter climatic conditions (Seo and Mendelsohn, 2008). Prices of agricultural outputs and inputs will also change, catalyzing changes in technology, infrastructure, policies, and governmental role in developing new farm technologies, crops, and breeds that are suitable for higher and drier climatic conditions (Van Passel et al., 2017).

4.4 Ecosystems

During dry years, ecosystems often suffer from water scarcity more than agricultural and urban sectors. Recent droughts highlighted the vulnerability of ecosystems to tight water allocation conditions and nearly 20 native species of fish were on the verge of extinction had the 2012-2016 drought have continued (Hanak et al. 2015). While this report does not directly model climate change impacts on ecosystems, lessons from recent droughts underscore some issues including lack of planning for managing ecosystems under extreme water scarcity conditions. Furthermore, current approaches for achieving minimum stream flows often lack flexibility, thereby increasing the costs of environmental water uses (Mount et al. 2017). Overpumping during dry years to compensate for surface water losses, particularly for agriculture, exacerbates water supply issues for ecosystems that rely groundwater and incidental flow into surface water streams. The 2014 Sustainable Water Management Act (SGMA), requiring critically overdrafted basins to achieve basinwide balance by 2040 may prevent some of these issues. Yet information on benefits from various management measures on ecosystem services is still unclear and merits further investigation.

4.5 Limitations and Future Work

Modeling crops under climate change using the approach in this paper provides useful insights for water management in agriculture and the potential adaptations that might occur, assuming approximate profit maximizing behavior. The approach also offers some challenges and limitations. These have been described in Medellín-Azuara et al. (2012), along with some sensitivity analyses to technological change and price effects. Overall results in cropping patterns and crop revenues hold for a wide range of yield changes, price, and technological change assumptions as presented in this paper. Further work will examine the potential changes in irrigation requirements on the water balance and their impact on water scarcity for agriculture by region. Yet estimated changes in crop requirements literature remains uncertain. Also, plant response to climate change elements including higher carbon concentrations, higher temperature, and water scarcity conditions is rather static and based on recent studies on yield response. However, advances in plant breeding will likely be an important form of adaptation in the near future and will likely dampen the adverse effects of climate change on crops, thereby decreasing the potential economic losses.

Our modeling of water costs for dairy feed production under climate change does not consider the potential heterogeneity in water price among farms when simulating hayand silage price and availabilty. We assume the same percentage change in water prices for farms growing alfalfa hay and corn silage. This simplification may introduce bias towards the estimate of the impact of water price change, especially when considering the different water demands from alfalfa hay production and silage production.

Modeling pasture supply for cattle under climate change using the estimated trend provides useful insights for potential climate change impact on pasture availability. The trend estimate for pasture acreage covered by snow, however, does not incorporate the potential change in pasture yield, pasture management, or the demand driven price change.

5: Conclusions and Policy Implications

Several findings arise from the present study for adaptation of crops, dairies and beef cattle to climate change:

1. Climate-related water shortages to agriculture range between 1.5% and 16% depending on the climate scenario modeled and the region. Overall, this effect is comparable to water shortage to agriculture during recent droughts.
2. Increased idle land due to historical or climate change conditions range between 6% and 10% of the base irrigated area in the model of 8.4 million acres. Increases in idle land are not only a result of climate factors, but also to urbanization, which dominates over water shortages except for the 30% rim inflow reduction scenario (30PCT).
3. Feed crops, grain, and field are more vulnerable to water shortages than fruits and vegetable crops. Sufficiently high prices in downstream sectors such as dairies and beef cattle will greatly influence future feed crop production decisions.
4. Overall, increased demand for specialty crops in California will drive revenues up compared to 2010 levels for all hydrologic scenarios considered. Decline in some crop yields may influence cropping decisions.
5. Dairy cattle may face higher prices of forage crops, but other pressures are likely to be more important in declining cow numbers.
6. There is likely to be more rangeland available for grazing, with fewer days covered by snow and perhaps more range forage available as increased growing degree days expand in summer range areas.
7. Results are consistent with previous work in that concentration value in California crops might be expected, yet the decrease in water supply for most climate scenarios is modest.

In light of these findings, some policy implications are worth mentioning. First, specialty crops including vegetables, non-tree fruits and orchards often have the economies of scale to purchase water from other agricultural users. Research on change in irrigation water requirements over various climate scenarios would be beneficial to quantify potential additional scarcity under climate change. Providing the institutional infrastructure to allow low environmental impact water exchanges among agricultural users to happen is a worthwhile strategy to examine in more detail.

Second, the 2012-2016 California drought highlighted the importance of groundwater reserves for weathering water scarcity particularly in agriculture. While making up surface water losses with additional groundwater pumping might dampen the drought effects for agriculture in the short term, externalities to residential (shallow) well users and future availability of groundwater for the basin users must be considered. If properly implemented, SGMA provides the regulatory framework to achieve long term groundwater sustainability at the basin scale. Yet some extreme measures including permanent land idling in the Central Valley might be needed.

Third, supply augmentation alternatives for agriculture including opportunistic groundwater recharge, surface storage, and increased conveyance infrastructure may improve the water supply system's resilience. Facilitating low environmental impact water exchanges among users may greatly reduce drought costs.

Fourth, impacts of SGMA and other environmental regulations may have a greater impact on shortage of water to agriculture than climate-related shortages. Early organization and planning to cope with climate change impacts and to facilitate adaptation will pay off.

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APPENDIX A: Demands Facing California Farm Commodities

The crop production model in this study takes into account potential increases or reductions in California crop demands. Depending on the crop, these changes in demand may or may not have an influence in crop prices and affect cropping decisions. The production model is able to calculate endogenously crop prices and cropping patterns. The two parameters of interest are shifts in the demand function over a long time horizon and the price elasticity of demand (the sensitivity of quantity demanded to price) over a long time horizon for each commodity considered. Before listing and explaining parameter choices for each commodity or group, development of the principles and theory behind parameter choice is necessary.

For the elasticity of demand, the major considerations are the share of California production in the relevant market and the substitutability of other products in that relevant market. First, the relevant market is the broadest location, time period and product specification into which a significant share of the California production is sold. For example, because exports are half or more than half of demand, the relevant market for California tree nuts (almonds, pistachios and walnuts) is the world market. Since these products are storable, seasonality does not separate markets. In contrast, corn silage is bulky and has high transport cost relative to the price, causing the markets for California-grown silage to be very local—within 70 miles of where the silage is grown. For fresh-market stone fruit, transportation is limited to the United States and storability is limited, resulting in a national market only existing during summer and early fall months.

The smaller the share of California product in the relevant market, the larger the demand elasticity. In the extreme case when California production is a tiny share, the elasticity of demand approaches minus infinity and California product has no impact on market price. For example, wheat produced in California is a tiny share of the relevant market because wheat is readily storable, widely transported and wheat grown in one place is substitutable with wheat of the same class grown in other places. Therefore, for example, durum wheat does not substitute for hard red winter wheat, California durum is substitutable in noodles for durum from other places. California production is significant in the tree nut world markets and is dominant for almonds, but production from other places is important for the other nuts (Iran for pistachios and many places for walnuts).

Once the relevant market and market share are considered, substitutability with other goods is the next determinant of elasticity of demand. Farm commodities may substitute to some degree with other products, especially other livestock feed crops. The more and closer substitutes the more negative the demand elasticity. For example, although they are not listed as identical products in the same market, the main substitutes for each individual nut type are other tree nuts and groundnuts.

Long term changes in food and commodity demand depends on the population growth, income growth and the income elasticity of demand, which translates growth in overall expenditures into growth in demand for quantities of specific commodities. Food and commodity demand grows roughly in proportion to population. Food and commodity demand grows positively, but much less than proportionately, with income growth.

For demand shifts for specific commodities, key drivers depend on specific factors of the relevant market. For corn silage, demand is primarily tied to the local dairy industry. That means growth in Central Valley corn acreage (which is mostly grown for silage) depends on growth (or not) in the California dairy industry, which depends on competition from dairy products produced in other regions. The other consideration for demand shifts is how price and competitiveness of substitute products varies. For example, alfalfa hay substitutes for corn silage in a dairy cow ration. So if local and regional hay production costs rise, and hence prices rise, the demand for silage will shift out (other things equal).

A.1 Specific Commodity Demand Shifts

With this background, let us consider specific California commodities and commodity groups.

Table A-1. Demand elasticities and demand growth facing California Crops.

Commodity	Relevant market	Demand elasticity	Main growth issues and drivers	Demand shift % by 2050
Alfalfa & hay	Mostly California 20% export	-2	Milk & compete Western hay	10
Almonds & pistachios	Global	-2	Income, compete other global sources	50
Corn silage	Central Valley	-1	Local milk growth	0
Cotton	Global	-100	Income, compete other sources & fabrics	0
Cucurbits	National & Canada	-2	US income & pop.	30
Dry beans	Global	-100	Income & pop. compete other sources	10
Fresh Tomatoes	National	-5	Income & pop. compete Mexico other	0

Grains	Global	-100	Income & pop. compete other sources	0
Onions & garlic	National	-5	Income & pop. compete other sources	20
Other orchard	National & global	-5	Income & pop. compete other sources	0
Other field	National & global	-100	Income & pop. compete other sources	0
Fresh fruit & vegetables	National	-2	Income & pop. compete other sources	30
Pasture	Local	-1	Local cattle & milk compete other beef, meats and dairy	0
Proc. tomato	Global	-5	Income & pop. compete other sources	30
Rice	Global	-100	Income & pop. compete other sources	10
Safflower	Global	-100	Income & pop. compete other sources and other oilseeds	0
Sugar beets	National	-100	Income & pop. compete other sources	0
Subtropical	National	-5	Income & pop. compete other sources	30

Vine	National & Global	-5	Income & pop. compete other sources	30

Note: Little or no relevant econometric estimation is available. Much of the demand growth potential depends on cross elasticities and judgement about supply shifts of competing sources.

APPENDIX B: Climate-Related Changes in Crop Yields

The potential effects of climate change on crop yields have been studied for more than a decade, using global and local data, historical meteorological information, and a wide range of models and tools (Shoups et al., 2010; Mehta et al., 2013; Deryng et al., 2016; Lobell et al., 2006, 2007; Jackson et al., 2011; Kerr et al., 2017). To model the potential effects of a warmer climate on yields, estimated reductions in crop yields are employed by the profit-maximizing crop production model to predict new cropping patterns following Medellín-Azuara et al. (2012). Potential effects on yields vary widely depending on the carbon concentration in the time horizon analyzed, precipitation and temperature. Other factors include the number of chill days in the year (which affects some perennials' dormancy) and the length of the season. The mix of these factors is not captured by a single study or model in California given the broad range of crop commodities, and local climate and soil conditions. Recognizing this limitation, in this section we provide estimates of crop yield changes under climate change, based on the published literature with emphasis on the Central Valley. Range of changes in yield by commodity and region is generally contained within a ±10% of the current crop yields. In some cases, warmer growing seasons and carbon concentrations may increase crop productivity. Projected sharp declines in yields may actually overstate harmful effects of climate change as no adaptation in crop varieties and technology is assumed. However, some crop groups such as citrus may see declines in yields. Kerr et al. (2017) provide a recent review on specialty crops for California. Table B-1 below presents a summary of potential climate-related yield changes for the Sacramento Valley and the San Joaquin Valley by year 2050.

Table B-1. Potential changes in crop yields due to climate warming by 2050.

Crop	Estimated Climate-Related Yield Change by 2050 (%)		Literature
	Sacramento Valley	San Joaquin Valley	
Alfalfa	4.9 to 6.3	7.5 to 5.4	Lee et al. 2009, Adams 2013
Almonds/Pistachios	-10	-10	Lobell and Field (2011)
Corn	-2.7 to 7.5	-2.8 to 2.5	Lee et al. 2009, Adams 2013
Cotton	N/A	-7.6 to -3.9	Lee et al. 2009, Adams 2013 Elias 2017

Cucurbits	-11.0	-11.0	Lobell et al. 2007 and Lobell and Field 2009, Kern 2017
Dry Bean	-5.1 to 12.3	-8.1 to -7.5	Adams et al 2003
Tomato Fresh	-2.6 to 2.4	-2.2 to 1.1	Lee et al. 2009, Adams 2003 Kerr 2017
Grain	-4.8 to -3.6	-6.4 to -1.4	Juvenal Campos 2017, Lee et al. 2009, Adams 2013
Onion Garlic	-11.0	-11.0	Lobell et al 2007 and Lobell and Field 2009, Kerr 2017
Orchards	5.0-5.6	2.5-5.0	Lobell et al 2007 and Lobell and Field 2009, Adams 2003
Field	-1.9 to 8.9	-6.1 to -3.7	Adams 2003
Vegetables	-11.0	-11.0	Lobell et al 2007 and Lobell and Field 2009, Kerr 2017
Pasture	-6.0	-6.0	Lobell et al 2007 and Lobell and Field 2009
Potato	-6.8	-9.4	Adams 2003
Tomato Processing	0.8	-0.7	Adams 2003, Lobell 2007
Rice	0.8 to 3.9	-4.3 to -2.8	Lee et al. 2009, Adams 2003, Elias 2007
Safflower	-9.3	0.0	Author calculations using DAYCENT
Sugar Beet	-5.6	-4.6	Adams 2003

Subtropical	1.8	-18.4	Adams 2003, Kerr 2017
Vine Crops	-4.9 to -2.2	-11 o -7.8	Lobell et al. 2007 and Lobel and Field 2009, Adams 2013

Most of the revised literature concur that warmer climate conditions will benefit alfalfa yields in California. Alfalfa can be more productive in warm climates when irrigated, yet temperatures above 30 °C may result in earlier flowering and reduced yield, poorer quality, and diminished suitability for lactating dairy animals (Al-Hamdani, 1990; Greenfield and Smith, 1973; Vough and Marten, 1971). In contrast, pasture yields may decrease from 6-7% depending on the geographic location. Recent studies by Lobell and Field (2011) predict about a 10% yield loss in almonds in the absence of adaptation.

Field crop yield change projections under climate change indicate only minor impacts in Sacramento valley. Adams (2003) predicts positive changes in yield estimation for sugar beet (5.6 %) in the Sacramento Valley but others predict the same in yield losses. Literature on cotton shows consistent losses of 6% for the San Joaquin valley, where it is currently grown in California.

For the truck (vegetables) crop group in California an 11% decrease in yields of both vegetables and allium (onion/garlic) was estimated for the Central Valley. Onions are chiefly cool-season crops that achieve optimal growth between 20 and 25 °C (Smith et al., 2011). Although our compilation indicates the negative effect of climate change in vegetables, it is unclear if lettuce production may be harmed by climate change (Lobell et al., 2007; Deschenes and Kolstad, 2011; Jackson et al., 2012). Some studies show a 7.8 % increase in lettuce by 2070-2099 (Deschenes et al., 2009) and 39 % increase in broccoli by 2070, due to warmer winters and northward range expansion (Deschenes and Kolstad, 2011).

Tomato yields are predicted to increase in Sacramento valley, but might slightly decrease in San Joaquin (Jackson et al. 2012, Lee et al. 2011). This trend is shared with Adams (2003) for processing tomatoes, but not for fresh tomatoes where this author estimates a 2.6% decrease in Sacramento versus a 2.2% drop in San Joaquin yields. Tomatoes are relatively heat-tolerant; however, overly warm average temperatures are especially harmful to tomatoes if they continue for days or weeks without a break (Sato et al., 2000); even brief extreme heat events can ruin tomato yields if they come at the wrong time (Ozores-Hampton et al., 2012). Processing tomatoes seem to experience a lower impact in the future scenarios. They are concentrated in the Central Valley where most are planted from greenhouse-grown seedlings from March through May. April max temperatures provide warm conditions that are beneficial for planting, which speeds seedling growth and increases yields (Hartz and Miyao, 1997).

Rice is cultivated only in seven counties in northern CA, where early planting in April or May increases yields. Planting early maximizes the use of solar radiation. It also diminishes potential exposure to temperatures above 35°C at flowering, which increases rice sterility (Satake, 1995). Surveyed studies agree on positive yield impacts in Sacramento Valley ranging from 0.1 to 3.9% and negative in San Joaquin for scenarios that go from -2.8 to -6%, although there is little rice production in the San Joaquin Valley.

Subtropical and citrus crops are mostly grown in southern California. According to Kerr et al. (2017) high temperatures harmful effect is less than that if frosting. Thus warmer temperature may reduce frosting threats for citrus (Kerr et al., 2017; Geisel and Unruh, 2003). Yields predicted for oranges in Sacramento valley foresee a minor increase, whereas San Joaquin valley may experience important rates of decrease in avocado (-6.6 %) and oranges (-18.4 %). By 2050, expected increases in winter minimum temperatures may roughly double the area climatically viable for navel orange production (Parker and Abatzoglou, 2016), but negative yield response to low minimum temperature in December and March may have a devastating impact of frost and freeze on citrus crops (Lobell et al., 2007).

For vine crops the findings are mixed. Table and wine grape yields may be relatively unchanged with a 2°C of temperature increase (Lobell et al., 2006), but the temperature increase will affect fruit quality in wine grapes (Nicholas et al., 2011). Area suited for high-quality wine grapes may decrease 70% by 2050 based on some estimates (Hannah et al., 2013). According to Lobell and Field (2011), warmer winters will cause some yield declines, but they can be partially absolved by warmer summers.

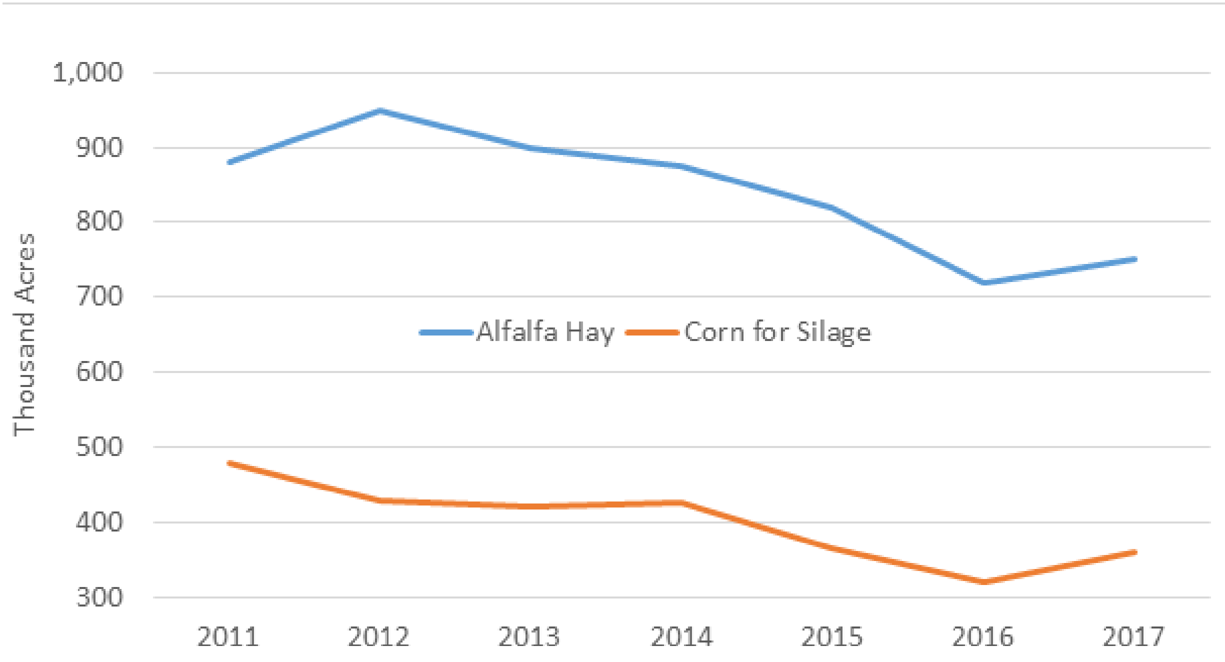
APPENDIX C: Modeling Feed Supply for Dairies

Table C-1 and Figure A-1 summarize the patterns of forage acreage from 2011 to 2017. These data are indicative of the impacts of increased warming causing less access of forage crops to land and, and especially irrigation water resource in the Central Valley.

Table C-1. California Forage Acreage (1,000 Acres).

Year	Hay Alfalfa	Other Hay	Hay All	Corn for Grain	Corn for Silage	Corn Total
2011	880	510	1,390	150	480	630
2012	950	600	1,550	180	430	610
2013	900	540	1,440	180	420	600
2014	875	500	1,375	95	425	520
2015	820	455	1,275	65	365	430
2016	720	480	1,200	100	320	420
2017	750	450	1,200	100	360	460

Source: USDA, NASS, Quickstats



Source: USDA, NASS, Quickstats

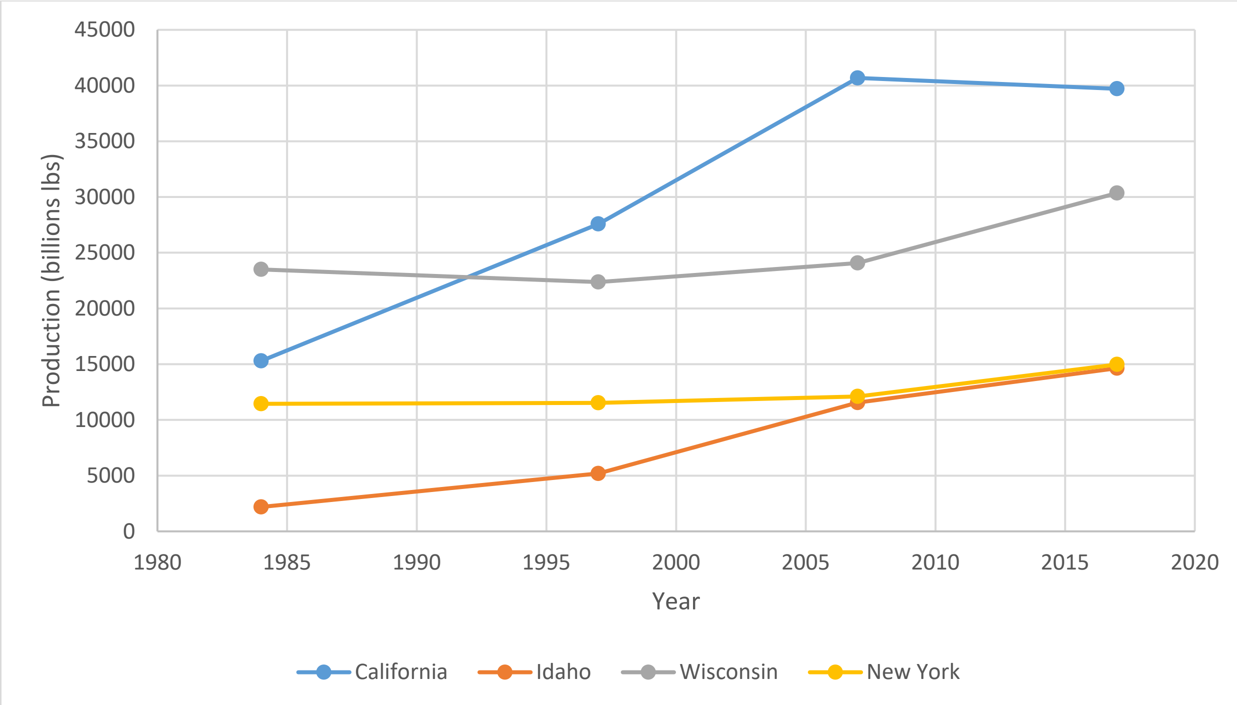
Figure C-1. California Alfalfa Hay and Corn for Silage Harvest Acreage (1,000 Acres).

APPENDIX D: California Milk in the Context of National and Global Markets

The California dairy industry is large and complex. Almost all Californian milk is processed in-state and about 20% of California-produced milk is used in California for beverage, soft or frozen products. Most other dairy products, including butter, milk powder, cheese, and whey are shipped out of California into national and global markets. That means farm milk prices are determined in those national and global markets and that many off-farm jobs in processing and transport hinge on the health of the California dairy farm industry (and vice versa). The importance of the world market implies that the demand elasticity facing California milk production is very elastic in the intermediate to long run. We argue that demand elasticity facing California produced milk is -5.0. The overall price elasticity of demand for dairy products, by contrast, is in the range of -0.5.

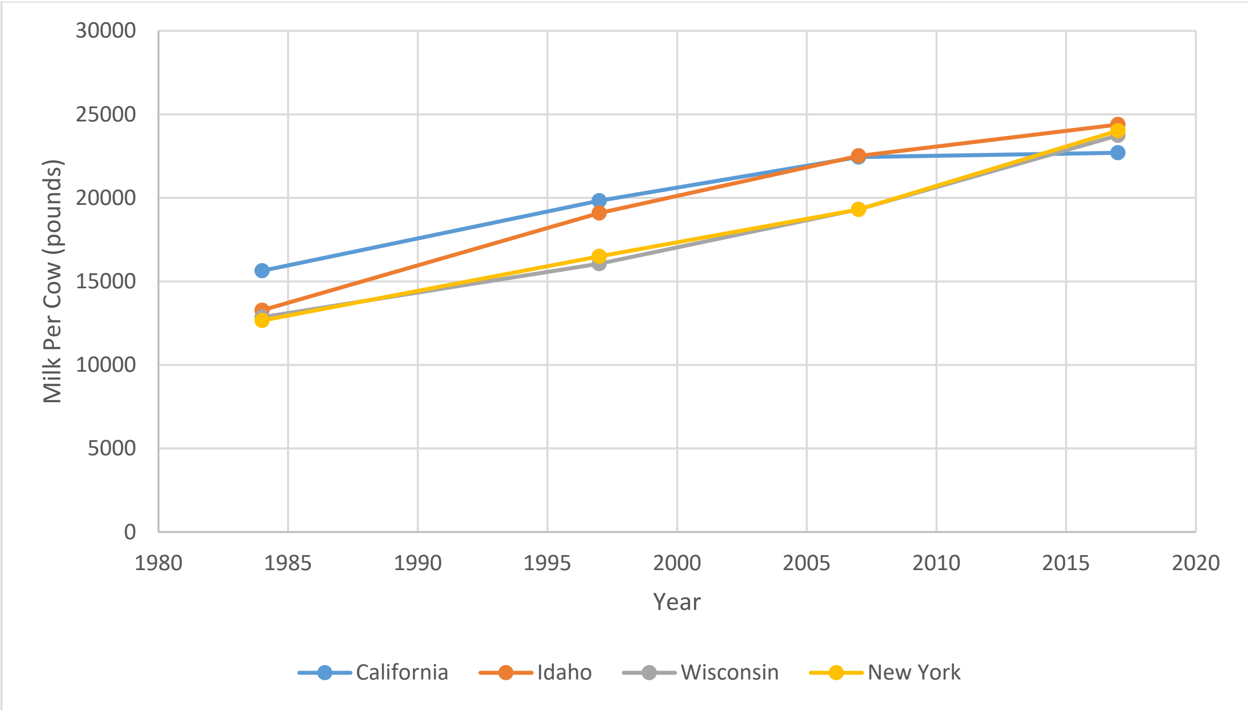
The U.S. farm value of milk was about $40 billion in 2017 and comprises about 10 percent of total U.S. farm cash receipts. Milk is among the important farm commodities in most states and is the top farm commodity in terms of cash receipts in several important agricultural states, such as California and Wisconsin. Milk is also the top farm commodity produced in several of the smaller agricultural states, such as Vermont. The major milk producing states range from New York and Pennsylvania in the East to Wisconsin and Minnesota the Midwest and Idaho, New Mexico and California in the West. Thus, the dairy industry is geographically diverse as well as large.

Two remarkable transformations in the milk industry have occurred in the past three decades. Figures D-1, D-2, and D-3 document these changes. First, from the early 1980s through 2007, milk production and productivity grew rapidly in the West as represented by California and Idaho. From 1984 through 2007, the number of cows doubled and milk production grew by two and one half times as milk production per cow rose by about 50 percent. Growth rates were even faster in Idaho which emerged as a major dairy state. Over that same time milk production stagnated in the East as represented by Wisconsin and New York, both of which experienced rapid increases in milk per cow but equally rapid declines in numbers of cows.



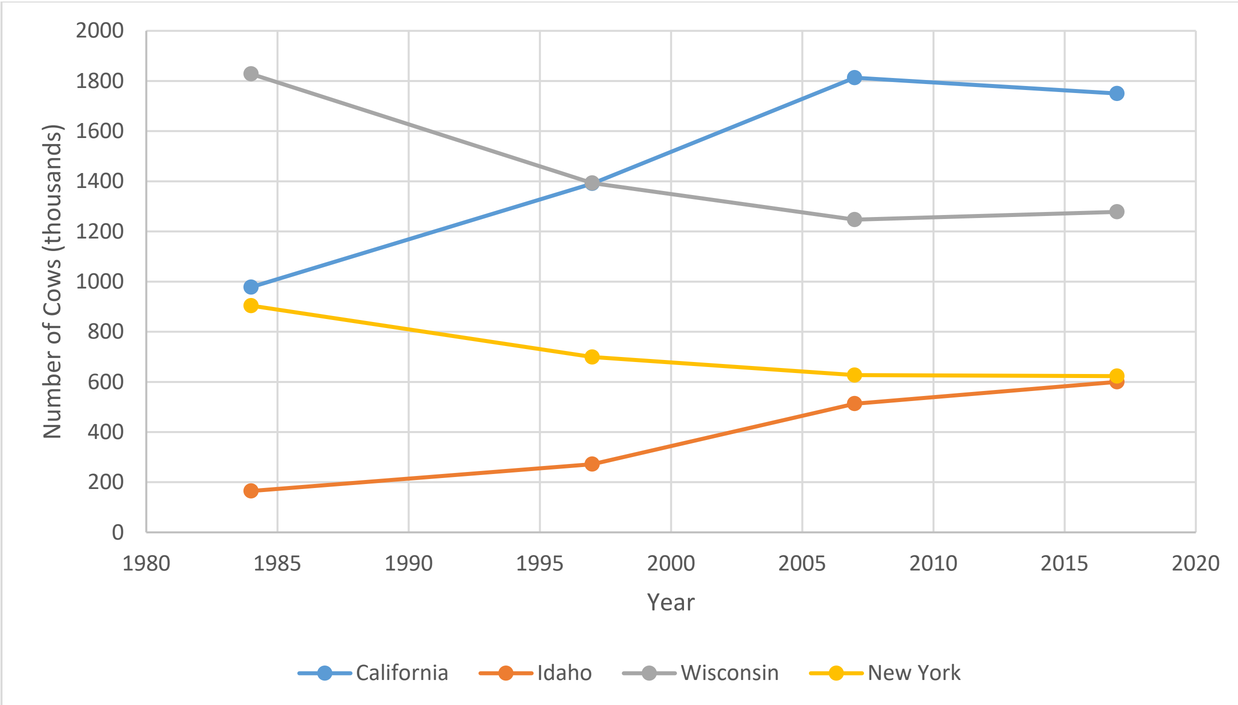
Source: USDA, NASS Quickstats.

Figure D-1. Annual milk production for major dairy states, 1984 through 2017



Source: USDA, NASS Quickstats.

Figure D-2. Milk per cow for major dairy states, 1984 through 2017.



Source: USDA, NASS Quickstats.

Figure D-3. Number of cows for major dairy states, 1984 through 2017.

In the decade since 2007, these trends have been reversed. California has had stagnant milk production with slight declines in cow numbers and slight gains in milk per cow. Idaho experienced much slower grow in cows and milk per cows than the previous period but added less than 30% to milk production compared to more than doubling in the previous decade. Remarkably, Wisconsin and New York held cow numbers steady as production per cow rose by about 25%. The result is that now California, still the largest dairy state by total production, has the lowest milk per cow of these four dairy production leaders.

Milk marketing cooperatives owned by dairy farmers account for about 84% of the milk produced and marketed in the United States. Cooperatives either process their farmer-owners milk or more often represents the marketing of member milk to other processors, without actually doing any processing themselves. Some cooperatives are large well known national or regional companies such as Dairy Farmers of America, Land O'Lakes, Dairy Farmers Incorporated. The top three cooperatives in California market about 80% of all milk in the State.

As with every agricultural commodity industry, features of the dairy industry are similar in some respects and differ in other respects from other farm commodity industries. As with eggs and some fruits and vegetables such as strawberries, for example, milk is perishable and harvested every day. Harvest timing for milk is even more crucial given animal welfare considerations. Milk is more homogeneous than many commodities, with the main differences in price determined by regulations and location. Organic milk (only a few percent) also commands much higher prices to cover the much higher costs of production.

Among major dairy states, milk per cow has risen most rapidly in the Midwest while, as noted, growth has slowed in the West, especially California, which used to be a leader in milk per cow. The price of milk has declined in real terms in line with growth of productivity. Since 1988 the national average "all-milk" price has fallen by more than a third from just under $27 per hundredweight (in 2017 dollars) to about $17 per hundredweight.

The increase in milk production, production per cow and reduced cows per farm has accompanied substantial increases in labor productivity and lower milk production costs. USDA data show that costs are substantially lower as number of cows rise from a few hundred cows or less to 1,000 cows or more. The farms with more cows rely on lower-cost hired labor for milking and routine chores. McDonald, Cessna and Mosheim (2016) provide details on the national patterns by herd size of dairy resource use and costs per hundredweight in their tables 4 through 6. They use the USDA Agricultural Resource Management Survey (ARMS) data to document strong economies of size. While these tables tell a revealing story, the causation is not as clear because size tends to be correlated with regions that may also influence costs. Moreover, for the smallest herds, those with less than 500 cows, a substantial part of costs are allocated to unpaid family labor.

The USDA data are certainly consistent with the observation that small dairy farms are leaving the industry or getting larger and large herds have been getting even larger. These patterns are also consistent with data from California that are compiled using very different methods. In the Southern San Joaquin Valley, herds of more than 1,500 cows have consistently lower costs per hundredweight than herds of 1,500 cows or less, even using similar technology in the same dairy-intensive region of California (CDFA dairy cost feedbacks). Hired labor costs are, of course, higher for larger herds and the share of hired labor of all labor is higher. But, total labor per unit of milk and labor costs per unit of milk are lower on the larger herds despite that fact that they pay a higher wage rate per hour.

APPENDIX: E. Modeling Impacts on Dairy of Higher Water Costs in Multistage Production Under Climate Change

According to Long et al. (2015), alfalfa hay production uses 18 cubic meters of irrigation water per hectare and yields 13,710 metric tons per hectare. When combined with water requirements, 764 cubic meters of water produces one metric ton of alfalfa hay. Based on Klonsky et al. (2015), corn silage uses 71 cubic meters of water per hectare and yields 11,171 metric tons of corn silage per hectare. The water input to corn silage ratio implies 1 cubic meters of water yield 155 metric tons of corn silage.

The prices for hay and silage are weighted feed cost based on 2015 Holstein Feed Summary reported by California Department of Food and Agriculture (CDFA) and the authors' calculation. We use a representative alfalfa hay price of 262 US dollars per metric ton and an estimated silage price of 80 US dollars per metric ton. Feed use is based on the assumed milk cow life cycle (Anderson and Sumner, 2016), milk yield from California Dairy Statistics reported by CDFA, the feed ration reported in the Holstein Feed Summary (CDFA, 2015), and authors' estimates. We find that a dairy cow on average consumes 1.67 metric tons of hay and 5.89 metric tons of silage per year, with annual milk production per milking cow of 10.6 metric tons within the standard 305 milking days per year. Thus, we estimate 0.22 metric tons of hay and 0.79 metric tons of silage are used to produce 1 metric ton of milk for a dairy cow, on average across its life cycle.

We use a price of milk in cheese production based on the minimum milk price for class 4b, which is 0.34 US dollars per kg (CDFA, 2016). According to California Dairy Statistics about 9.8 kilograms of milk produces one kilogram of cheese. Based on CDFA manufacturing cost reports in 2014, processors spend 0.52 US dollars on non-milk inputs to produce one kilogram of cheese. The cheese price is estimated based on the sum of the milk cost and non-milk cost, given prices and production ratios, which is 3.81 US dollars per kilogram. We assume the demand facing California cheese is very elastic due to the high degree of substitution from cheese produced outside California. California's dairy processing plants accounts for almost 40% of U.S. dairy exports (Matthews, et.al, 2016). The cheese produced in California faces high degree of substitution from the cheese produced in the rest of the United States and elsewhere. We use -5 as the demand elasticity for California cheese in the long run. Table E-1 shows parameters used to estimate impacts in the multi-stage cheese production.

Table E-1: Estimated statistics for roughage, milk and cheese productions in California.

Rough estimates	Unit	Value
Water in Hay	m^3/metric ton	764
Water in Silage	m^3/metric ton	155
Hay in Milk	metric ton/metric ton	0.22
Silage in Milk	metric ton / metric ton	0.79
Milk in Cheese	kg/kg	9.80
Hay Price	$/ metric ton	262
Silage Price	$/ metric ton	80
Milk Price	$/kg	0.34
Non-milk Cost in Cheese	$/kg	0.52
Estimated Cheese Price	$/kg	3.81
Demand Elasticity for Cheese	-	-5

Source: Long et al. (*2015*); Klonsky et al. (*2015*); Anderson and Sumner (*2016*); *California Department of Food and Agriculture* (*2015*) and author estimates.

Because much alfalfa hay is produced in the North Sacramento Valley or other places and corn silage is produced in the San Joaquin Valley, we assume different water prices for the two crops. We use 0.04 US dollars per cubic meter in alfalfa hay production, and 0.08 US dollars per cubic meter in silage production. We simulate the impact of higher water prices by increasing water price from 0.04 US dollars per cubic meter to 0.08 US dollars per cubic meter for alfalfa hay production, and from 0.08 US dollars per cubic meter to 0.16 US dollars per cubic meter for silage production.

Here we show the key equations used in the numerical simulations.

$$\Delta P_h = (\frac{1}{\lambda_1})\Delta P_w$$

$$\Delta P_s = (\frac{1}{\lambda_2})\Delta P_w$$

$$\Delta P_m = \left(\frac{1}{\alpha_1}\right)\Delta P_h + \left(\frac{1}{\alpha_2}\right)\Delta P_s$$

$$\Delta P_c = (\frac{1}{\omega})\Delta P_m$$

The subscript *"h"* represents hay and the subscript *"s"* represents silage. The subscription *"w"* stands for water. The subscript *"h"* and *"s"* represent hay and silage, respectively. Subscript *"m"* stands for milk and *"c"* stands for cheese. *"P"* is price and *"Q"* is the quantity of the corresponding output. λ_1 represents the cost share of water usage in hay production, and λ_2 represents the cost share of water in silage production. α_1 and α_2 represent the cost share of hay and silage in milk production, respectively. The variable *"ω"* stands for the cost share of milk in cheese production. We consider proportional changes as:

$$d(\ln P_c) = \frac{\Delta P_c}{P_c{}^*}$$

where "P_c*" is the equilibrium prices for cheese in the global market, and "ΔP_c" stands for the changes in cheese prices due to water price change under climate change. The equilibrium prices and quantity in cheese market is:

$$d(\ln Q_c{}^*) = \epsilon d(\ln P_c{}^*)$$

where "ϵ" is the demand elasticity for cheese produced using California milk in the global market.

A higher water cost causes an increase in the cost of production of hay and silage. We assume the marginal cost of non-water inputs in crop production do not change and the non-forage inputs in milk production do not change. We also assume that the non-milk inputs in milk production are constant. Hence, moving through the vertical chain of cheese production, the marginal cost of cheese production increases by a fixed amount determined by the increase in the cost of irrigation wat

APPENDIX F: Modeling California Rangeland

Rangeland Definition

California has about 56 million acres rangeland. "Rangelands" are defined as all non-forest vegetation cover types characterized by a predominance of herbaceous and shrub species, including desert lands (CDFF, 1988). The 56 million acres rangeland includes all lands in California with at least some grazing potential. However, the link between the rangeland area to the amount of forage available for grazing depends on the vegetation types and the biophysical characteristics of the rangeland such as the climate, water source, slope, and soil types.

To get the 56 million acres rangeland, we start with California total area by land-cover types. There are about 101 million acres total land area in California, including open water. The top three largest areas by land cover types in California are shrubland, forests and grass/pasture that are about 43.14%, 23.03% and 10.96% of total area in California. The land used for crops including fallow cropland is about 9.7 million acres that is about 9.63% of total area. The land developed is about 6.8 million acres that includes areas with a mixture of constructed materials and vegetation, e.g. single-family housing units, parks, golf courses and apartment complexes. In Table F-1, we show the area by land cover types in California. Areas with potential grazing includes 1) some areas covered by forests, particularly area covered by deciduous forest, 2) most of the shrubland, and 3) grass/pasture area listed in Table F-1.

Table F-1: California land distribution in terms of land-cover types in 2017.

	Acres	Share
Total California Area	101,213,730	
Land-cover types		
Some of the Lands Used for Crops	9,749,266	9.63%
Aquaculture	347	0.00%
Open Water	1,284,769	1.27%
Perennial Ice/Snow	8,353	0.01%
Areas Developed: Open Space, Low, Medium & High Intensities	6,832,426	6.75%
Deciduous, Evergreen & Mixed Forests	23,307,568	23.03%
Shrubland	43,665,332	43.14%
Grass/Pasture	11,095,753	10.96%
Barren	4,685,117	4.63%

Woody and Herbaceous Wetlands	584,798	0.58%

Notes:

(1) Some of the lands used for crops include fallow cropland.

(2) The land-cover types listed are based on categories reported in Cropland Data Layer.

(3) Cropland Data Layer is based on sources with different dates. It is based on satellite data collected during growing seasons for most crops in 2017.

(3) The non-agricultural land-cover classes, including open water, perennial ice/snow, area developed, Deciduous, evergreen and mixed forests, shrubland, grass/pasture, barren and woody and herbaceous wetlands, are entirely dependent upon the National Land Cover Database 2011 (NLCD 2011).

Sources: Cropland Data Layer, National Agricultural Statistics Service, accessed on 4/10/2018: https://nassgeodata.gmu.edu/CropScape/

Within the 56 million acres rangeland area, about one third of the rangeland is covered by desert scrub. The second largest rangeland area is annual grassland that covers about 13% of the total rangeland. Woodland including blue oak-foothill pine, blue oak woodland, coast oak woodland, and valley oak woodland, is another large rangeland, which covers about 15% of total rangeland. In Table F-2, we listed the rangeland by vegetation cover types. Twenty-six vegetation habitats defined in the California Wildlife Habitat Relationships Database (CWHR) (Mayer and Laudenslayer, 1988) were classified as rangelands based on the Society for Range Management's definition of rangelands. Rangeland includes natural grasslands, savannas, shrublands, most deserts, tundra, alpine communities, and wet meadow. Forest habitats include pinon-juniper and juniper habitat that may be grazed. The CWHR habitat classification is determined by the habitat/vegetation with more than twenty-five percent coverage by area.

Table F-2: California rangeland acreage by vegetation types in 2012.

	Acres	
All Rangeland in California	55,793,671	
Vegetation Types	**Acres**	**Share**
Alpine-Dwarf Shrub	180,554	0.32%
Annual Grassland	7,139,474	12.80%
Alkali Desert Scrub	3,682,214	6.60%
Bitterbrush	40,832	0.07%
Blue Oak-Foothill Pine	3,673,912	6.58%
Blue Oak Woodland	2,823,104	5.06%

Coast Oak Woodland	921,189	1.65%
Chamise-Redshank Chaparral	2,931,161	5.25%
Coastal Scrub	1,658,012	2.97%
Desert Riparian	48,183	0.09%
Desert Scrub	18,621,225	33.38%
Desert Succulent Shrub	807,561	1.45%
Desert Wash	858,611	1.54%
Joshua Tree	58,490	0.10%
Juniper	2,181,063	3.91%
Low Sage	620,407	1.11%
Mixed Chaparral	3,189,754	5.72%
Montane Chaparral	577,092	1.03%
Montane Riparian	66,300	0.12%
Perennial Grassland	88,669	0.16%
Pinyon-Juniper	1,636,222	2.93%
Palm Oasis	3,030	0.01%
Sagebrush	3,063,483	5.49%
Valley Oak Woodland	633,203	1.13%
Valley-Foothill Riparian	163,048	0.29%
Wet Meadow	126,876	0.23%

Notes: The vegetation types considered as rangeland are based on the Range Management's definition.

Sources: Calculations based on National Gap Analysis Project (GAP 2011), USGS.

Table F-3: Rangeland acreages in Major Land Resource Areas in California.

Major Land Resource Areas	Acres	Share
All Rangeland in California	55,787,263	100%
Central California Coastal Valleys	552,683	0.99%

Central California Coast Range	9,565,567	17.15%
California Delta	11,017	0.02%
Sacramento and San Joaquin Valleys	2,600,026	4.66%
Sierra Nevada Foothills	4,311,826	7.73%
Southern California Coastal Plain	703,579	1.26%
Southern California Mountains	4,540,030	8.14%
Klamath and Shasta Valleys and Basins	2,728,099	4.89%
Sierra Nevada Mountains	1,998,985	3.58%
Southern Cascade Mountains	365,164	0.65%
Malheur High Plateau	769,975	1.38%
Carson Basin and Mountains	984,710	1.77%
Fallon-Lovelock Area	68,159	0.12%
Southern Nevada Basin and Range	3,837,977	6.88%
Mojave Desert Basin and Range	15,903,702	28.51%
Lower Colorado Desert	5,591,308	10.02%
Sonoran Basin and Range	1,471	0.00%
Coastal Redwood Belt	272,958	0.49%
Siskiyou-Trinity Area	980,029	1.76%

Notes: The total acreage of rangeland in California is different from Table F-1 due to the coordinate system difference between MLRA and rangeland habitat dataset. The re-projected MLRA polygons do not perfectly match the rangeland area in California. Rangeland along the coastline of California is omitted for rangeland computation in Table F-3.

Sources: Calculation based on National Gap Analysis Project (GAP 2011), MLRA boundaries by USDA Agriculture Handbook 296, 2006.

Table F-3 shows the spatial distribution of rangeland across Major Land Resource Areas (MLRAs) in California. A MLRA defined by National Resources Conservation Service is a geographic area that is characterized by a particular pattern of soils, climate, water resources, land uses, and types of farming. The Mojave Desert Basin and Range has the largest rangeland area that is about 29% of the total rangeland area. The Central California Coast Range has the second largest area of rangeland that is about 17% of the total rangeland area in California. The link between forage availability and rangeland acreage across different MLRAs are very different due to the different vegetation types and biophysical characteristics across areas.

The rangeland defined in this study is a very different concept from the pastureland category reported by the U.S. Census of Agriculture. The Census of Agriculture reported about 14.4 million acres of pastureland in 2012. The pastureland includes areas owned/rented by a farm or ranch, including 1) permanent pastureland, 2) woodland pastured and 3) cropland pastured. Areas grazed by public permits on per-head basis or private rangeland area grazed but not reported as pasture were not included in the pastureland category by the Census of Agriculture. The 14.4 million acre pastureland did not include most of public rangeland grazed in California.

Two federal agencies, the U.S. Forest Service and the Bureau of Land Management (BLM) administer most of the public land for grazing. The Forest Service administered about 14.6 million acres grazing allotments with 924 individual permits for grazing in 2016. There were 357,048 animal unit months (AUMs) for livestock authorized for grazing, with 79,258 cows and cow-calf pairs (332,702 authorized AUMs), 193 bulls (1,200 authorized AUMs), and 2,097 yearling feeder cattle (4,117 authorized AUMs). The average number of months for beef cows grazing on U.S. Forest Service land is about 3.2 months.

The BLM administered about 8.4 million acres grazing allotments with 632 permits active in 2016. There were 237,154 AUMs authorized for livestock grazing, with 197,541 AUMs for 56,662 head of cow-calves and bulls, and 13,636 AUMs for feeder cattle (4,320 head). The average number of months for cow-calves and bulls grazing on BLM land is 2.7 months.

Table F-4: Beef cow grazing and forage consumption in 2016.

Forage Sources	(1) Reported Acre Grazed or Authorized for Grazing (Million)	(2) Number of Beef Cow (Thousand)	(3) AUMs for Beef Cow (Thousand)
Total Grazed Rangeland	37.4	600	9,360[7]
U.S. Forest Service Allotments (2016)	14.6[3]	79	332.7[2]
	(39.0%)[8]	(13.2%)	(3.5%)
BLM Allotments (2016)	8.4[3]	41	147.3[2]
	(22.5%)	(6.8%)	(1.6%)
Private Pastureland[5] (2012)	14.4	480□	8,602.5[6]
	(38.5%)	(80.0%)	(91.9%)
Hay	N/A[1]	N/A[1]	292.5[6]
			(3.1%)

Notes:

[1] N/A represents information not available.

[2] The AUMs reported by BLM and Forest Service are authorized for cattle. The actual utilized AUMs may be smaller than the authorized AUMs.

[3] The Forest Service and BLM area authorized for grazing is based on allotment polygons published by Forest Service and BLM.

[4] The 480 thousand head is the difference between total beef cow in California and the number of cows authorized to graze on Forest Service and BLM in 2016.

[5] The private rangeland is based on pastureland from Census of Agriculture (2012). It may include other public grazing but leased by public permits not based on per-head basis. The amount of public grazing falls into this category is very small.

[6] The annual hay consumption by beef cows were calculated based on pasture-hay ratio of 1:31 from calculation based on UC Davis Cost Study of cow-calf operation (Forero et al., 2017).

[7] One beef cows are considered as 1.3 animal unit months. The number is adopted from the Forest Service permits.

[8] Values in the parentheses are 1) shares of reported acreage over the sum of the all reported acreage grazed or authorized for grazing; 2) shares of beef cow head over the sum of total number of beef cow head in California; 3) shares of AUMs consumed by beef cows over the sum of AUMs required by beef cows in California.

Sources: Calculation based on individual permits provided by U.S. Forest Service and Rangeland Administration System (BLM), U.S. Census of Agriculture (2012), allotment boundaries by Forest Service (2018), and U.S. Department of Interior, BLM (2017), Forero et al., 2017.

Despite the large public grazing land, the private pastureland is the most important forage source for beef cows in California. Based on authors' calculation, about 92% of the total forage consumed by 600,000 beef cows in 2016 were from private rangeland. Table F-4 shows the beef cow grazing and forage consumption in 2016. About 3.5% of the total AUMs consumed by beef cows were from grazing on Forest Service land, and 1.6% of the total AUMs consumed by beef cows came from grazing on BLM land. The grazing on private rangeland offered about 92% of the AUMs and the rest AUMs came from hay. Regardless of the large forage source from private rangeland, only 38.5% of the reported rangeland area grazed or authorized for grazing is private. About 20% of the beef cows spent 3.3 months grazing on public land in 2016.

Cattle Relevant Rangeland Regions

There is relative little information about spatial distributions of beef cows within counties in California. We constructed a beef cow inventory list by MLRAs using county level beef cow inventories from the 2012 Census of Agriculture and 2012 January cattle survey by National Agricultural Statistics Service. The beef cows within each county are allocated using the acreage of rangeland defined by the twenty-six habitats listed in Table F-2. We identified the rangeland area owned by 1) Forest Service and BLM rangeland, and by 2) private and other public agencies, using the California Protected Area Database (CPAD, 2017). In the next step, we weighted the rangeland acreage in the two categories using the AUM ratio as 1:9 from Table F-

4. We allocated the beef cows using the weighted proportion of rangeland across MLRAs within each county. Table F-5 shows number and share of beef cows by MLRAs.

Table F-5: Estimated number and share of beef cows across Major Land Resource Areas in 2012.

Major Land Resource Areas	Number of Beef Cows	Share
All Rangeland in California	576,270	100%
Central California Coastal Valleys	13,518	2.32%
Central California Coast Range	187,644	32.24%
California Delta	849	0.15%
Sacramento and San Joaquin Valleys	82,738	14.21%
Sierra Nevada Foothills	111,437	19.14%
Southern California Coastal Plain	1,309	0.22%
Southern California Mountains	9,017	1.55%
Klamath and Shasta Valleys and Basins	60,850	10.45%
Sierra Nevada Mountains	18,410	3.16%
Southern Cascade Mountains	8,062	1.38%
Malheur High Plateau	13,026	2.24%
Carson Basin and Mountains	4,589	0.79%
Fallon-Lovelock Area	2,667	0.46%
Southern Nevada Basin and Range	10,978	1.89%
Mojave Desert Basin and Range	19,310	3.32%
Lower Colorado Desert	7,633	1.31%
Sonoran Basin and Range	4	0.00%
Coastal Redwood Belt	3,249	0.56%
Siskiyou-Trinity Area	20,979	3.60%

Notes:

(1) The number of beef cows is weighted county level beef cow inventory using rangeland area over lapped in the Major Land Resource Areas and Counties.

(2) Public rangeland acreage and private rangeland acreage are weighted as 1:9 based on Table F-4.

Sources: Calculations based on National Gap Analysis Project (GAP) (2011), National Geospatial Data Assets (NGDA), USGS (2012) and MLRA boundaries by USDA Agriculture Handbook 296 (2006); and county level beef cow inventory from U.S. Census of Agriculture (2012) and January cattle survey from National Agricultural Statistics Service (2012), California Protected Areas Database (CPAD) – www.calands.org (August 2017)

The Census of Agriculture (2012) did not report beef cow inventories for seventeen counties (out of fifty-eight counties) that own about one fourth of the beef cows in California. We used the January cattle survey (NASS, 2012) and number of operation by beef cow inventories from Census of Agriculture (2012) to reconstruct the missing inventories of beef cows. The steps include: 1) computing the state average of beef cow inventories across different operation sizes; and 2) calculating the inventories by operation sizes using state average from step 1 and the reported number of operations by the Census of Agriculture.

Table F-5 shows the number and the share of beef cows by MLRAs in California in 2012. About 32% of the beef cows in 2012 were allocated in Central California Coastal Range. Rangeland in the Central California Coastal Range usually can be grazed year-round. The ranches are far from high elevation rangeland for summer forage. Ranches feed cows hay during summer when the season is dry and the forage availability is low. Sierra Nevada Foothill rangeland fed about 19% beef cows in 2012. Typically ranches along the Sierra Nevada Foothills move cattle to higher elevation public lands for summer grazing (George, Frost, and McDougald, 2016), such as Sierra Nevada Mountains and Southern Cascade Mountains. Klamath and Shasta Valleys and Basins had 10% of beef cows in 2012. The ranches in the area move the cattle up to higher elevation public rangeland such as Siskiyou-Trinity Area during the summer. Another source of forage for beef cows grazing in Klamath and Shasta Valleys is the area in Coastal Redwood Belt where grazing may happen after logging.

APPENDIX G. Modeling Pasture Availability Under Historical Climate Conditions

Historical Climate on Rangeland

California rangeland is wet in the winter. The cow- weighted state level precipitation in January is about 95 mm. The past 97 years from 1920 to 2016 saw a 0.17% annual decrease in January precipitation. The acreage-weighted state level precipitation is smaller due to large rangeland area in the desert. All January precipitations by MLRAs showed decreasing trends from 1920 to 2016, except the desert area, Lower Colorado Desert and Sonoran Basin and Range. We did not include July precipitation in Table G-10 because the July precipitation is very small. The July trends in precipitation vary across the areas but the change in the absolute amount of precipitation is also small.

Areas providing important summer forage were greatly affected by snow. Most of the rangeland areas in Sierra Nevada Mountains and Southern Cascade Mountains had snow. About 80% of the areas have heavy snow with more than 30 days of snow per year. The area with average snow cover days greater than 30 days is about 80%. Rangeland in Klamath and Shasta Valleys and the mountain area Siskiyou-Trinity Area were also substantially affected by snow. About 96% of the rangeland in Klamath and Shasta Valleys had more than 30 days of snow. About 50% of the rangeland in Siskiyou-Trinity area was covered by snow for more than 30 days per year.

Table G-1: Average acreage of rangeland with snow across Major Land Resource Areas in California from 1920 to 2016.

Major Land Resource Area	Average Acres with snow	Average Acres with more than 30 days of snow	Acres averaging more than 30 days of snow
All Rangeland in California	27,765,430	10,057,674	9,961,558
Central California Coastal Valleys	110,526	2,859	341
Central California Coast Range	3,621,166	241,978	185,500
California Delta	1,951	0	0
Sacramento and San Joaquin Valleys	356,391	781	579
Sierra Nevada Foothills	2,363,659	302,515	316,570
Southern California Coastal Plain	94,407	7,507	4,144
Southern California Mountains	2,801,987	699,931	675,139
Klamath and Shasta Valleys and	2,725,002	2,531,671	2,632,006

Basins			
Sierra Nevada Mountains	1,942,031	1,522,568	1,524,669
Southern Cascade Mountains	357,275	293,634	312,225
Malheur High Plateau	769,069	691,424	740,464
Carson Basin and Mountains	984,218	943,926	975,968
Fallon-Lovelock Area	66,925	35,937	225
Southern Nevada Basin and Range	3,553,665	1,813,674	1,836,390
Mojave Desert Basin and Range	6,546,140	437,210	207,455
Lower Colorado Desert	489,707	30,340	8,295
Sonoran Basin and Range	167	0	0
Coastal Redwood Belt	95,685	10,097	8,908
Siskiyou-Trinity Area	885,459	491,622	532,680

Notes:

(1) The average acres with snow are rangeland with snow averaged over the years for each Major Land Resource Area (MLRA). Within a MLRA, the acreages are summed together across rangeland areas.

(2) The average acres with more than 30 days of snow are rangeland with more than 30 days of snow averaged over the years for each MLRA. Within a MLRA, the acreages are summed together across rangeland areas with more than 30 days of snow.

(3) The acres averaging more than 30 days of snow are sum of rangeland acreage with average of more than 30 days of snow within each MLRA. Average snow days are calculated for each rangeland area to select rangeland under this category.

(4) The Major Land Resource Area is based on the boundaries by USDA Agriculture Handbook 296 (2006), see Figure 5-A. Valley areas may include hillsides near the valley floor, which may have high elevation and have snow cover for more than 30 days.

Sources: Calculations by authors based on the VIC output of SWE provided by Mao, Nijssen, and Lettenmaier (2015) and Xiao, Nijssen, and Lettenmaier (2016) and rangeland area defined using National Gap Analysis Project (GAP), National Geospatial Data Asset (NGDA), USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)

Table G-2: Shares of rangeland area with snow across Major Land Resource Areas in California from 1920 to 2016.

Major Land Resource Area	Share of Average Acres with Snow	Share of Average Acres with More Than 30 Days of snow	Share of Acres Averaging More Than 30 Days of snow
All Rangeland in California (cow-weighted)	51.1%	21.5%	21.8%
All Rangeland in California (acre-weighted)	49.80%	18.01%	17.84%
Central California Coastal Valleys	20.0%	0.5%	0.1%
Central California Coast Range	37.9%	2.5%	1.9%
California Delta	17.7%	0.0%	0.0%
Sacramento and San Joaquin Valleys	13.7%	0.0%	0.0%
Sierra Nevada Foothills	54.8%	7.0%	7.3%
Southern California Coastal Plain	13.4%	1.1%	0.6%
Southern California Mountains	61.7%	15.4%	14.9%
Klamath and Shasta Valleys and Basins	99.9%	92.8%	96.5%
Sierra Nevada Mountains	97.2%	76.2%	76.3%
Southern Cascade Mountains	97.8%	80.4%	85.5%
Malheur High Plateau	99.9%	89.8%	96.2%
Carson Basin and Mountains	100.0%	95.9%	99.1%
Fallon-Lovelock Area	98.2%	52.7%	0.3%
Southern Nevada Basin and Range	92.6%	47.3%	47.8%
Mojave Desert Basin and Range	41.2%	2.7%	1.3%
Lower Colorado Desert	8.8%	0.5%	0.1%
Sonoran Basin and Range	11.4%	0.0%	0.0%
Coastal Redwood Belt	35.1%	3.7%	3.3%
Siskiyou-Trinity Area	90.4%	50.2%	54.4%

Notes: The shares are areas divided by the total rangeland area within each Major Land Resource Area.

Sources: Calculations by authors based on the VIC output of SWE provided by Mao, Nijssen, and Lettenmaier (2015) and Xiao, Nijssen, and Lettenmaier (2016) and rangeland area defined using National Gap Analysis Project (GAP), National Geospatial Data Asset (NGDA), USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)

The mountain areas including Sierra Nevada Mountains and Southern Cascade Mountains that provide important summer forage for cattle grazing on Sierra Nevada foothills, saw substantial decrease in areas covered by snow. These two regions saw a decrease in area with snow by about 0.02 % annually and the area with more than 30 days of snow by 0.05% annually. Rangeland in northern California also experienced decreases in areas with, including regions of Klamath and Shasta Valleys and Basins, and Siskiyou-Trinity Area. The Klamath and Shasta Valleys and Basins saw a decrease in area with snow by 0.002 % annually and Siskiyou-Trinity Area saw a decrease of 0.07 % annually. For areas with more than 30 days of snow, the Klamath and Shasta Valleys and Basins saw a decrease of 0.03 % annually and Siskiyou-Trinity Area saw a decrease of 0.24% annually.

Table G-3: Percentage change in rangeland acreage with snow across Major Land Resource Areas in California from 1920 to 2016.

Major Land Resource Area	Share of Beef Cows	% Change in Acres with Snow	% Change in Acres with More Than 30 Days of snow
All Rangeland in California (cow-weighted)	100%	-0.16%	-0.031%
All Rangeland in California (acre-weighted)	100%	-0.082%	-0.033%
Central California Coastal Valleys	2.32%	-1.33%	-4.25%
Central California Coast Range	32.24%	-0.76%	-1.44%
California Delta	0.15%	-1.38%	N/A
Sacramento and San Joaquin Valleys	14.21%	-1.13%	-0.21%
Sierra Nevada Foothills	19.14%	-0.27%	-0.36%
Southern California Coastal Plain	0.22%	-0.18%	-0.81%
Southern California Mountains	1.55%	-0.02%	-0.16%
Klamath and Shasta Valleys and Basins	10.45%	0.00%	-0.03%

Sierra Nevada Mountains	3.16%	-0.02%	-0.05%
Southern Cascade Mountains	1.38%	-0.02%	-0.05%
Malheur High Plateau	2.24%	0.00%	-0.02%
Carson Basin and Mountains	0.79%	0.00%	0.00%
Fallon-Lovelock Area	0.46%	-0.02%	-0.05%
Southern Nevada Basin and Range	1.89%	-0.06%	-0.26%
Mojave Desert Basin and Range	3.32%	-0.01%	-1.06%
Lower Colorado Desert	1.31%	-0.16%	-0.11%
Sonoran Basin and Range	0.00%	-6.07%	N/A
Coastal Redwood Belt	0.56%	-0.71%	-2.10%
Siskiyou-Trinity Area	3.60%	-0.07%	-0.24%

Notes:

(1) N/A represents unable to compute the trend because no area was covered by snow during the period.

(2) The percentage changes in acres with snow are acreage-weighted percentage change in acres with snow on rangeland areas within each MLRA. Rangeland areas within same MLRA are assumed to share the same percentage change.

(3) The state-level percentage changes in rangeland with snow cover are based on regional estimate weighted by the share of area with snow cover and the beef cow share in each region.

Sources: Calculations by authors based on the VIC output of SWE provided by Mao, Nijssen, and Lettenmaier (2015) and Xiao, Nijssen, and Lettenmaier (2016) and rangeland area defined using National Gap Analysis Project (GAP), National Geospatial Data Asset (NGDA), USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)

Table G-4: Average days with snow on rangeland per year in Major Land Resource Areas in California from 1920 to 2016.

Major Land Resource Areas	Average Days with Snow on All Rangeland	Average Days with Snow on Rangeland Ever with Snow for at Most 30 Days	Average Days with Snow on Rangeland with Snow for More Than 30 Days
All Rangeland in California (cow-weighted)	24.18	6.34	60.73

All Rangeland in California (acre-weighted)	21.05	5.92	68.89
Central California Coastal Valleys	1.07	1.13	34.25
Central California Coast Range	3.47	2.66	46.36
California Delta	0.02	0.02	N/A
Sacramento and San Joaquin Valleys	0.38	0.37	36.85
Sierra Nevada Foothills	7.76	4.04	54.71
Southern California Coastal Plain	1.19	1.15	67.69
Southern California Mountains	15.37	6.95	64.87
Klamath and Shasta Valleys and Basins	96.60	21.28	99.35
Sierra Nevada Mountains	123.68	13.89	157.83
Southern Cascade Mountains	93.28	10.87	107.24
Malheur High Plateau	83.95	25.59	86.27
Carson Basin and Mountains	121.44	28.44	122.27
Fallon-Lovelock Area	24.54	24.49	40.03
Southern Nevada Basin and Range	48.28	12.67	87.10
Mojave Desert Basin and Range	3.85	3.01	71.89
Lower Colorado Desert	0.77	0.93	56.61
Sonoran Basin and Range	0.00	0.01	N/A
Coastal Redwood Belt	4.18	3.56	36.63
Siskiyou-Trinity Area	53.98	11.86	89.36

Notes:

(1) N/A represents there is no rangeland has more than 30 days of snow for Sonoran Basin and Range, and California Delta.

(2) Average days with snow for rangeland areas are snow days averaged over the years.

(3) Average days with snow for rangeland within each MLRA are acreage-weighted average of snow days averaged over years.

Sources: Calculations by authors based on the VIC output of SWE provided by Mao, Nijssen, and Lettenmaier (2015) and Xiao, Nijssen, and Lettenmaier (2016) and rangeland area defined using National Gap Analysis Project (GAP), National Geospatial Data Asset (NGDA), USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)

For the rangeland in mountain areas, such as Sierra Nevada Mountains, the heavy snow areas are seeing 20 less days with snow on rangeland. As the mountainous areas provide important summer forage, less snow cover days will help supporting longer grazing season for cattle.

Table G-5: Percentage Change in days with snow on rangeland across Major Land Resource Areas in California from 1920 to 2016.

Major Land Resource Areas	% Change in Days with Snow on All Rangeland	% Change in Days with Snow on Rangeland Ever with Snow for at most 30 Days	% Change in Days with Snow on Rangeland with Snow for More Than 30 Days
All Rangeland in California (cow-weighted)	-0.81%	-0.98%	-0.28%
All Rangeland in California (acre-weighted)	-0.54%	-0.66%	-0.24%
Central California Coastal Valleys	-2.58%	-2.61%	-0.88%
Central California Coast Range	-1.26%	-1.49%	-0.60%
California Delta	-4.52%	-4.52%	N/A
Sacramento and San Joaquin Valleys	-1.40%	-1.44%	0.14%
Sierra Nevada Foothills	-0.41%	-0.59%	-0.25%
Southern California Coastal Plain	-0.63%	-0.94%	0.00%
Southern California Mountains	-0.28%	-0.53%	-0.14%
Klamath and Shasta Valleys and Basins	-0.07%	-0.22%	-0.06%
Sierra Nevada Mountains	-0.14%	-0.24%	-0.13%
Southern Cascade Mountains	-0.10%	-0.38%	-0.10%
Malheur High Plateau	-0.09%	-0.01%	-0.09%
Carson Basin and Mountains	-0.10%	-0.10%	-0.10%
Fallon-Lovelock Area	0.01%	0.01%	-0.10%
Southern Nevada Basin and Range	-0.35%	-0.47%	-0.33%
Mojave Desert Basin and Range	-0.32%	-0.33%	-0.31%

Lower Colorado Desert	-0.26%	-0.31%	0.20%
Sonoran Basin and Range	-4.05%	-4.05%	N/A
Coastal Redwood Belt	-1.66%	-2.04%	-0.72%
Siskiyou-Trinity Area	-0.22%	-0.90%	-0.15%

Notes:

(1) N/A represents unable to compute the trend because no area was covered by snow for more than 30 days annually for Sonoran Basin and Range, and California Delta.

(2) The percentage changes in days with snow for MLRAs are acreage-weighted percentage changes for rangeland areas within each MLRA. Rangeland areas are assumed to have same percentage change within a MLRA.

Sources: Calculations by authors based on the VIC output of SWE provided by Mao, Nijssen, and Lettenmaier (2015) and Xiao, Nijssen, and Lettenmaier (2016) and rangeland area defined using National Gap Analysis Project (GAP), National Geospatial Data Asset (NGDA), USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)

Table G-6. Average maximum Normalized Difference Vegetation Index in spring and fall on California rangeland across Major Land Resource Areas from 1982 to 2016.

Major Land Resource Areas	Average Max NDVI in Spring	Average Max NDVI in Fall
All Rangeland in California (cow-weighted)	0.40	0.28
All Rangeland in California (acre-weighted)	0.28	0.21
Central California Coastal Valleys	0.52	0.36
Central California Coastal Range	0.46	0.31
California Delta	0.52	0.27
Sacramento and San Joaquin Valleys	0.42	0.26
Sierra Nevada Foothills	0.49	0.31
Southern California Coastal Plain	0.38	0.25
Southern California Mountains	0.41	0.32
Klamath and Shasta Valleys and Buttes	0.28	0.23
Sierra Nevada Mountains	0.36	0.33
Southern Cascade Mountains	0.39	0.36

Malheur High Plateau	0.21	0.14
Carson Basin and Mountains	0.21	0.19
Fallon-Lovelock Area	0.15	0.11
Southern Nevada Basin and Range	0.16	0.13
Mojave Desert Basin and Range	0.12	0.10
Lower Colorado Desert	0.11	0.09
Sonoran Basin and Range	0.18	0.21
California Coastal Redwood Belt	0.59	0.45
Siskiyou - Trinity Area	0.51	0.43

Notes:

(1) The average value of max NDVI is acreage-weighted average across rangeland units, and over the years.

(2) Spring includes March, April and May. Fall months includes September, October and November. **Sources**: Calculation by authors based on 32-day NDVIs from Landsat satellite data from 1982 to 2016, available at Google Earth Engine, https://explorer.earthengine.google.com/#search/tag%3Alandsat%2032%20day%20%20ndvi.

The mountain areas such as Sierra Nevada Mountains and Southern Cascade Mountains, are getting greener faster than other MLRAs for spring and fall. Snow may be one of the contributors. For instance, when snow melts earlier in the spring, the forage plants start growing earlier with warmer temperature and benefit from water runoff from the snowmelt. The satellites are more likely to capture greenness in the spring and the maximum greenness of forage plants in spring is likely to be greener. When the snow falls later in the fall, the forage plants will have a longer growing season with rainfalls and cool temperature. The satellite may be more likely to capture greener rangeland area and the maximum greenness of forage plants in fall is likely to be greener.

Table G-7: Percentage change in maximum Normalized Difference Vegetation Index in spring and fall on rangeland across Major Land Resource Areas in California from 1982 to 2016.

Major Land Resource Area	% Change in Max NDVI in Spring	% Change in Max NDVI in Fall
All Rangeland in California (cow-weighted)	0.17%	0.20%
All Rangeland in California (acre-weighted)	0.09%	0.13%

Central California Coastal Valleys	0.12%	0.39%
Central California Coastal Range	0.11%	0.16%
California Delta	0.13%	-0.15%
Sacramento and San Joaquin Valleys	0.11%	0.13%
Sierra Nevada Foothills	0.24%	0.20%
Southern California Coastal Plain	-0.36%	0.14%
Southern California Mountains	-0.14%	-0.20%
Klamath and Shasta Valleys and Buttes	0.31%	0.30%
Sierra Nevada Mountains	0.32%	0.47%
Southern Cascade Mountains	0.13%	0.27%
Malheur High Plateau	0.64%	0.21%
Carson Basin and Mountains	0.30%	0.47%
Fallon-Lovelock Area	0.38%	0.05%
Southern Nevada Basin and Range	0.41%	0.22%
Mojave Desert Basin and Range	0.06%	0.12%
Lower Colorado Desert	-0.27%	-0.16%
Sonoran Basin and Range	0.72%	1.18%
California Coastal Redwood Belt	0.26%	0.57%
Siskiyou - Trinity Area	0.17%	0.42%

Notes:

(1) The percentage change is the acreage-weighted average of percentage change in max NDVI values across MLRAs per year.

(2) Areas within a MLRA are assumed to have the same percentage change per year.

(3) The percentage change is the trend estimate of seasonal maximum NDVI using pooled-OLS for each MLRA.

Sources: Calculation by authors based on 32 days-NDVI from Landsat satellite data from 1982 to 2016, available at Google Earth Engine, https://explorer.earthengine.google.com/#detail/LANDSAT%2FLE07%2FC01%2FT1_32DAY_NDVI

Table G-8: Percentage changes in acreage of rangeland with snow across Major Land Resource Areas in California from by 2050.

Major Land Resource Areas	Share of Beef Cows	% Change in acreage with Snow	% Change in Acreage with More Than 30 Days of snow
All Rangeland in California (cow-weighted)	100%	-5.74%	3.56%
Central California Coastal Valleys	2.32%	-35.6%	-100%
Central California Coast Range	32.24%	-33.6%	-10.4%
California Delta	0.15%	N/A	N/A
Sacramento and San Joaquin Valleys	14.21%	10.0%	10.0%
Sierra Nevada Foothills	19.14%	-12.0%	-20.0%
Southern California Coastal Plain	0.22%	-5.2%	-17.2%
Southern California Mountains	1.55%	-19.6%	-20.0%
Klamath and Shasta Valleys and Basins	10.45%	-2.0%	-32.4%
Sierra Nevada Mountains	3.16%	-4.8%	-8.4%
Southern Cascade Mountains	1.38%	-3.2%	-21.6%
Malheur High Plateau	2.24%	-2.0%	-23.2%
Carson Basin and Mountains	0.79%	-0.4%	-11.2%
Fallon-Lovelock Area	0.46%	-6.8%	N/A
Southern Nevada Basin and Range	1.89%	-7.6%	-16.0%
Mojave Desert Basin and Range	3.32%	-9.6%	-10.0%
Lower Colorado Desert	1.31%	18.0%	-4.4%
Sonoran Basin and Range	0.00%	N/A	N/A
Coastal Redwood Belt	0.56%	-24.4%	4.8%
Siskiyou-Trinity Area	3.60%	-14.0%	-24.4%

Notes:

(1) N/A represents areas without snow cover or unable to estimate the linear with only one or two years with snow cover area.

(2) The percentage changes in acres with snow are acreage-weighted percentage change in acres with snow on rangeland areas within each MLRA. Rangeland areas within same MLRA are assumed to share the same percentage change.

(3) Results are based the average estimate of the four climate models: CanESM2, CNRM-CM5, HadGEM2-ES and MIROC5.

Sources: Calculations by authors based on the VIC output of SWE provided by LOCA and rangeland area defined using National Gap Analysis Project (GAP), National Geospatial Data Asset (NGDA), USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)

Table G-9: Total changes in days with snow on rangeland across Major Land Resource Areas in California by 2050.

Major Land Resource Areas	Change in Days with Snow on All Rangeland by 2050	Change in Days with Snow on Rangeland Ever with Snow for at Most 30 Days by 2050	Change in Days with Snow on Rangeland with Snow for More Than 30 Days by 2050
All Rangeland in California (cow-weighted)	-19.64%	-13.72%	-24.02%
Central California Coastal Valleys	-14.02%	-14.16%	-25.64%
Central California Coast Range	-22.77%	-20.30%	-30.00%
California Delta	N/A	N/A	N/A
Sacramento and San Joaquin Valleys	26.32%	29.73%	-19.02%
Sierra Nevada Foothills	-18.30%	-10.89%	-25.26%
Southern California Coastal Plain	-19.33%	-8.70%	-41.81%
Southern California Mountains	-21.21%	-16.26%	-24.22%
Klamath and Shasta Valleys and Basins	-22.43%	-22.13%	-22.44%
Sierra Nevada Mountains	-14.64%	-15.98%	-14.60%
Southern Cascade Mountains	-22.28%	-20.15%	-22.31%
Malheur High Plateau	-16.22%	-7.31%	-16.33%
Carson Basin and Mountains	-12.38%	-8.72%	-12.38%

Fallon-Lovelock Area	-9.13%	-9.15%	-8.02%
Southern Nevada Basin and Range	-15.43%	-18.47%	-14.95%
Mojave Desert Basin and Range	-8.05%	-4.98%	-16.83%
Lower Colorado Desert	-3.90%	-2.15%	-29.50%
Sonoran Basin and Range	N/A	N/A	N/A
Coastal Redwood Belt	-16.51%	-15.45%	-20.07%
Siskiyou-Trinity Area	-24.19%	-22.68%	-24.36%

Notes:

(1) N/A represents unable to compute the trend because there were no days with snow on rangeland in Sonoran Basin and Range, and California Delta under the climate scenario.

(2) The changes in days with snow for MLRAs are acreage-weighted changes for rangeland areas within each MLRA. Rangeland areas are assumed to have same changes within a MLRA.

(3) Results are based on the average of the four climate models: CanESM2, CNRM-CM5, HadGEM2-ES and MIROC5.

Sources: Calculations by authors based on the VIC output of SWE provided by Mao, Nijssen, and Lettenmaier (2015) and Xiao, Nijssen, and Lettenmaier (2016) and rangeland area defined using National Gap Analysis Project (GAP), National Geospatial Data Asset (NGDA), USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)

Appendix Table G-8 shows the estimate of rangeland area with snow across MLRAs in California by 2050. In Sierra Nevada Mountains, the area with snow will be declining by 4.8% by 2050. The area with more than 30 days of snow per year will decline by 8.4%. In Southern Cascade Mountains, the area with snow will decline by 3.2%. The area with more than 30 days of snow will decline by 21.6% by 2050. In Northern California, Klamath and Shasta Valleys will see an increase in areas with snow for about 2.0% by 2050. The area with more than 30 days of snow will decrease by 32.4%. Siskiyou-Trinity Area will see a decrease of 14.0% for rangeland area with snow, and a decrease of 24.4% for areas with more than 30 days of snow by 2050.

Table G-9 shows the trend in days with snow on rangeland across Major Land Resource Areas from 2010 to 2050. Rangeland with heavy snow area (area with at most 30 days of snow) will see a faster decline in days with snow than light snow area (area with more than 30 days of snow). Rangeland in the mountainous area, such as Klamath and Shasta Valleys and Basin, and Southern Cascade Mountains, are experiencing rapid decline in snow cover days. By 2050, rangeland with heavy snow in Klamath and Shasta Valleys and Basin will have about 23 less days with snow.

Table G-10: January precipitation and estimated trends across Major Land Resource Areas for California rangeland from 1920 to 2016.

Major Land Resource Areas	Average of Jan Precip. (mm)	% Change in Jan Precip. (trend)
All Rangeland in California (cow-weighted)	94.95	-0.17%
All Rangeland in California (acre-weighted)	68.72	-0.09%
Central California Coastal Valleys	149.286	-0.23%
Central California Coast Range	105.247	-0.13%
California Delta	77.077	-0.28%
Sacramento and San Joaquin Valleys	75.774	-0.11%
Sierra Nevada Foothills	104.017	-0.27%
Southern California Coastal Plain	78.915	-0.05%
Southern California Mountains	98.082	-0.05%
Klamath and Shasta Valleys and Basins	62.240	-0.23%
Sierra Nevada Mountains	137.249	-0.23%
Southern Cascade Mountains	116.668	-0.06%
Malheur High Plateau	50.810	-0.31%
Carson Basin and Mountains	77.446	-0.10%
Fallon-Lovelock Area	39.100	-0.05%
Southern Nevada Basin and Range	41.710	-0.38%
Mojave Desert Basin and Range	28.336	-0.05%
Lower Colorado Desert	21.573	0.38%
Sonoran Basin and Range	13.564	0.55%
Coastal Redwood Belt	204.491	-0.24%
Siskiyou-Trinity Area	209.234	-0.15%

Notes:

(1) The precipitation (mm) includes rainfall and snowfall converted to water equivalent.

(2) The average January precipitation is the average precipitations over the years. Within each Major Land Resource Areas, the average precipitations are weighted by acreage across rangeland areas.

(3) The percentage change in January precipitation is the acreage-weighted average of the percentage changes in January precipitations for all rangeland areas within each Major Land Resource Area.

Sources: Calculation by authors based on historical daily precipitation provided by Mao, Nijssen, and Lettenmaier (2015) and Xiao, Nijssen, and Lettenmaier (2016), and rangeland area defined using National Gap Analysis Project (GAP) by USGS, and vegetation habitat classification is based on California Wildlife Habitat Relationships Database (Mayer and Laudenslayer, 1988)