Title

Climate Change and the Agricultural Sector in the San Francisco Bay Area: Changes in Viticulture and Rangeland Forage Production Due to Altered Temperature and Precipitation Patterns

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CLIMATE CHANGE AND THE AGRICULTURAL SECTOR IN THE SAN FRANCISCO BAY AREA

Changes in Viticulture and Rangeland Forage Production Due to Altered Temperature and Precipitation Patterns

A White Paper from the California Energy Commission's California Climate Change Center

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DISCLAIMER

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PREFACE

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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In 2003, the California Energy Commission's PIER Program established the California Climate Change Center to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions.

For more information on the PIER Program, please visit the Energy Commission's website http://www.energy.ca.gov/research/index.html or contract the Energy Commission at (916) 327-1551.

ABSTRACT

Climate change has the potential to alter the San Francisco Bay Area's agricultural production, a $2 billion industry. Two of the top sectors, wine and ranching, are examined in this paper. Downscaled models suggest that forage production in Bay Area rangelands may be enhanced by future conditions in most years, at least in terms of peak standing crop. However, the timing of production is as important as its peak, and altered precipitation patterns could mean delayed germination and earlier senescence, resulting in shorter growing seasons. An increase in the frequency of extremely dry years also increases the uncertainty of forage availability. Similarly, wine grape yields are projected to increase throughout much of the Bay Area, but wine grape quality may decline substantially under future climate conditions, as the crop ripens earlier during hotter months. The implications for these shifts in wine grape and forage production are that the aspects of Bay Area agriculture most sensitive to climate change are not yields, but subtler nuances of production such as quality and timing. Adaptive measures will need to be taken to maintain the economic viability of these enterprises.

Keywords: viticulture, rangeland, forage production, agriculture, climate change, Bay Area

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Section 1: Introduction

The San Francisco Bay Area (Bay Area) comprises $2 billion of California's $36 billion/year agricultural industry (NASS 2008). Wine grapes are the most valuable crop in the Bay Area, accounting for nearly half of the value of agriculture in this region, at $917 million. Animal products (including beef and other meats, as well as dairy) make up the second most valuable sector of Bay Area agriculture, worth $316 million (Table 1). Furthermore, when considering agricultural area rather than economic value, pasture ranks far ahead of the rest, taking up over 80 percent of the 1.6 million acres of total agricultural land in the Bay Area. Rangeland habitats (grassland, shrubland, and savannah) that could be used for grazing occupy much of the rest of the Bay Area's open space. Wine grapes, meanwhile, account for nearly half of the remaining (240,000 acres of non-pasture) agricultural area (Table 2). Therefore, the effects of climate change on wine grape and rangeland forage production deserve special attention, as these two industries play such a major role in Bay Area agriculture.

Table 1. Value and Acreage of the Top 10 Crops in the San Francisco Bay Area Region

Commodity	Value	Acres
Grapes*	$917,261,900	106,924
Animal Products	$315,935,960	N/A
Nursery Products	$323,823,700	N/A
Mushrooms	$65,797,000	158
Vegetables	$58,122,800	5,836
Hay	$40,802,300	67,784
Flowers	$35,639,900	N/A
Tomatoes	$28,963,200	11,220
Pasture	$25,025,200	1,290,179
Walnuts	$23,852,700	8,352

*All counties produce exclusively wine grapes, except for Contra Costa County, which is listed as "undetermined," and likely includes a significant amount of table grapes. See also Table 2, below.

Source: NASS 2008

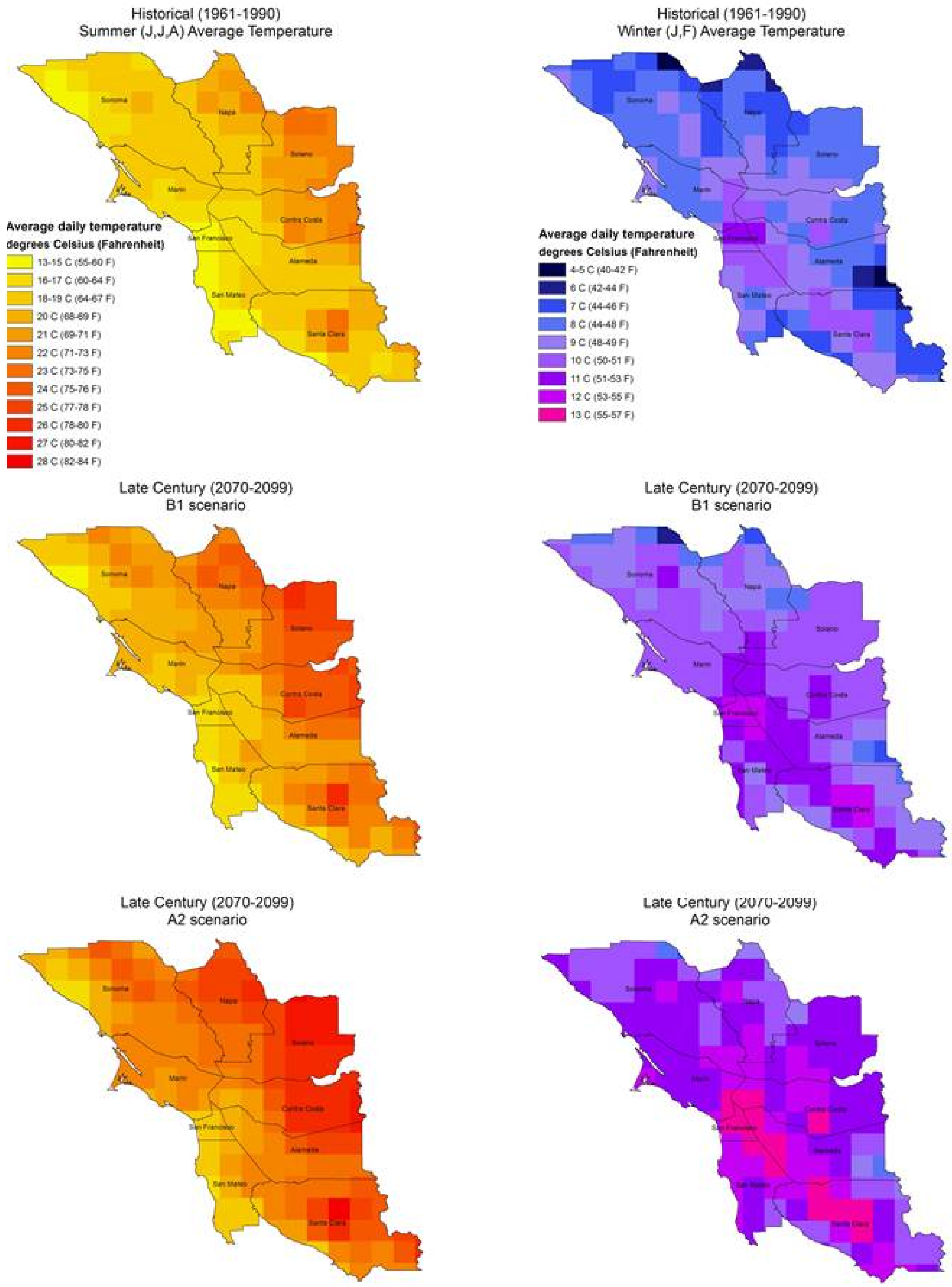
Table 2. Value and Acreage of Wine Grapes and Animal Products/Pasture

County	Wine/Grapes			Animal Products		
	Value	Acreage	% (Non-pasture) Ag. Acreage	Value (Animals + Pasture)	Acreage (pasture/range)	% Total Ag. Acreage
Alameda	$6,455,000	1,916	30.5	$10,752,000	189,000	96.8
Contra Costa	$6,140,000	1,910	7.2	$16,561,960	175,790	86.8
Marin	$755,700	192	5.8	$62,760,700	154,810	97.9
Napa	$472,606,600	42,338	98.8	$4,349,700	(not reported)	
San Mateo	$550,000	98	3.0	$1,611,000	30,300	90.3
Santa Clara	$6,110,000	1,550	7.9	$10,439,500	181,625	90.2
Solano	$8,095,000	4,021	3.0	$59,188,900	202,826	60.1
Sonoma	$416,549,600	54,899	82.0	$175,297,400	355,828	84.2
Total	**$917,261,900**	**106,924**	**45.3**	**$340,961,160**	**1,290,179**	**80.9**

Source: NASS 2008

For California as a whole, temperatures over the next century have been projected to rise between 1.7°C and 3.0°C (3.0°F to 5.5°F) for a lower emissions scenario, and 4.4°C to 5.8°C (7.9°F to 10.4°F) for a higher emissions scenario (Cayan et al. 2006). Downscaled data for the Bay Area show a lower rise in temperatures, from between 1.5°C and 3.0°C (2.7°F to 5.5°F) by 2100 for lower emissions and 2.5°C to 4.4°C (4.5°F to 7.9°F) for higher emissions, though considerable variation exists within the region (Figure 1).

Warming trends are also not spread evenly over the season or even the day; due to warming over the north Pacific, the greatest warming in coastal California occurs in the spring and at night (Nemani et al. 2001). In fact, some evidence suggests that summer maximum temperatures are declining in coastal California, due to a "sea-breeze" effect driven by warming of interior areas (Lebassi et al. 2009). However, other analysis indicates that fog frequency on the coast is declining, which would ultimately lead to low-level warming in coastal regions (Johnstone and Dawson 2010). In either case, overall average temperatures may not adequately capture the true nature of warming for the Bay Area, and may in fact dramatically underestimate climate change impacts (White et al. 2006).


Historical (1961-1990)
Summer (J,J,A) Average Temperature

Historical (1961-1990)
Winter (J,F) Average Temperature

Late Century (2070-2099)
B1 scenario

Late Century (2070-2099)
B1 scenario

Late Century (2070-2099)
A2 scenario

Late Century (2070-2099)
A2 scenario

Source: Cayan et al.

Figure 1. Historical (1961–1990) and Projected (2070–2099) Average Temperatures for Summer (June, July, August) and Winter (January, February) Months in the Bay Area. Temperatures reflect means of four downscaled global climate models (CNRM CM3, GFDL CM2.1, NCAR CCSM3.0, and NCAR PCM1).

Understanding Bay Area agriculture’s vulnerability to future climate conditions requires first identifying the vineyard and grazing regions most exposed to climate threats and the aspects of wine grape and rangeland forage production most sensitive to those threats. This paper therefore consists of two parts: (1) a review of the literature relevant to wine and rangelands, to identify the sensitive aspects of production, with a focus on the Bay Area where such research exists; and (2) models for the effect of climatic change on wine and forage production, utilizing established relationships between these variables of interest and climate variables to identify the region’s most exposed to climate threats. This project will lay the foundation for further efforts toward a full vulnerability assessment of this system, which may include exploring the adaptive capacity of different agricultural operations and determining how management decisions can help mitigate the impacts of climate change on our agricultural systems.

Section 2: Literature Review

2.1 Effects of Climate Change on Range Livestock Production

Very little research has investigated the effects of climate change on animal production in California. One of the only such studies, Hayhoe et al. (2004), found that rising temperatures could reduce milk production by as much as 7 to 10 percent (for the Intergovernmental Panel on Climate Change's lower-emissions B1 scenario) and 11 to 22 percent (for the A1fi scenario) by the end of the century for the top 10 dairy counties in the state. Sonoma and Marin Counties rank eleventh and fourteenth, respectively, in milk production, well below leading counties in the San Joaquin valley (NASS 2008). However, as these Bay Area counties are projected to remain cooler than many of the top dairy counties (for example, Fresno, San Joaquin and San Bernardino Counties), they may not experience the declines predicted by Hayhoe et al. (2004).

While research on the effects of climate change on animal production should ultimately address the change in yields of the end-products (meat and milk), animal production systems are complex and different aspects may respond to climate in different ways. Preliminary steps must therefore be taken to understand the effects of climate change on the components of animal production systems—the animal feed or forage and the animals themselves. Forage quantity and quality are concerns that can be addressed through the study of climate effects on plant physiology and ecology. Heat stress and pests or disease dynamics are additional concerns that should be taken into account at the individual animal level.

Climate change has the potential to impact all realms of animal production systems, including rangeland and irrigated pasture, as well as feed crops like hay, corn, and silage. However, it is rangeland (which, unlike pasture, is not irrigated) that accounts for the majority of agricultural land-use in the Bay Area, and though both dairy and beef production in the Bay Area rely on supplemental feed during certain times of year, such feed often comes from well outside the Bay Area. As this review is limited in scope to the Bay Area, discussion of climate change effects in this review will therefore focus on range livestock production. Most rangeland in the Bay Area is grazed by beef cattle, with the exception of Marin and Sonoma Counties, where over half of animal production is dairy cattle that do utilize pasture and rangeland (NASS 2008; Agboh-Noameshie and Al-Ajjawi 2004).

2.1.1 Forage Quantity

The full extent of climate change impacts on rangeland forage production in California and the Bay Area in particular is uncertain. Shaw et al. (2009) modeled the impact of forecasted changes in precipitation patterns on California rangeland production, concluding that areas of the state suitable for cattle grazing would shift, as some become wetter and others become drier, depending on the climate model. In terms of both forage production and precipitation, the PCM showed an increase for Northern California and a decrease for the Central Coast and Sierra Foothills; the GFDL showed large declines throughout the state, with only modest increases in parts of the North Coast and higher elevations in the Sierras. At a statewide level, Shaw et al. predicted that forage production would decline between 14 and 58 percent, corresponding to a reduction in annual profits from cattle ranching of between $22 million and $92 million by 2070.

Despite this statewide trend, the results of Shaw et al. (2009), for the Bay Area in particular, suggested that the impacts would be more positive, with forage production increases projected for Santa Clara, Alameda, Contra Costa, Solano, and Napa Counties (Marin and Sonoma Counties were not included in the model). However, the authors acknowledged that their model may overestimate the effects of precipitation, since it did not incorporate warming. This study also assumed a close relationship between annual precipitation and forage production. While that is often true, near average production can occur in low rainfall years if precipitation is well distributed, and low annual production can occur in wet years if precipitation is poorly distributed or if temperatures are below normal, as is often associated with wet weather (George et al. 2010).

Better forecasts of rangeland production would include both precipitation and temperature in the same model. Field data at several sites in Northern California show forage yield and resulting cattle weight gain were both highly positively correlated with temperature (George et al. 1988). Temperature is the main constraint in California grassland productivity during the winter, and strong relationships have been found between biomass production and accumulated degree-days (George et al. 1988). Warming also has the potential to alter precipitation patterns (Backlund et al. 2008), and has been shown to increase soil water content by accelerating plant senescence (Zavaleta et al. 2003b). In fact, grassland ecophysiology may be less responsive to changes in total quantity of rainfall than shifts in seasonal patterns of rainfall (Chou et al. 2008). Early-season precipitation alone explained 49 percent of the variability in shoot-growth at the Hopland field station, just North of the Bay Area (Murphy 1970), although additional data reduced this explanatory power to 34 percent (George et al. 1989). Late-season precipitation also has a pronounced impact on Bay Area and North Coast grassland production, shown by increased shoot growth resulting from experimental water additions in the late spring (Suttle et al. 2007; Zavaleta 2003a).The combined effects of the timing and amount of precipitation and seasonal temperature patterns will influence growing season length, plant phenology, and productivity in rangelands (George et al. 2001a).

No models incorporating the impact of warming on California rangeland production yet exist. Hanson et al. (1993) predicted increases in spring plant production and an extension of the growing season with climate change in the Great Plains. However, these authors warned that increases in variance may be more important than the mean effect, because of the effect of unpredictability on grazing management. Uncertainty regarding plant growth results in uncertainty in stocking decisions. Hanson et al. (1993) found that changes in variance typical of their simulations suggested that carrying capacities would need to be shifted from about 6.5 to 9.0 hectare (ha) per animal to maintain a 90 percent confidence of not overstocking. They also pointed out that more intense management would increase operating costs, and therefore may cancel out any benefits in forage production.

In contrast to the Great Plains, where the growing season begins in the spring months following winter dormancy, Bay Area rangeland growing season begins with the first fall rains and ends with soil moisture depletion in the spring months. Climate change in the Bay Area may be more comparable to that found in the similarly Mediterranean climate of southern Australia. For this region, Howden et al. (2008) projected lower pasture production as a result of lower precipitation and higher temperatures. Incorporating the effects of warming into models on rangeland production in California, and the Bay Area in particular, is an important step in understanding how climate change will affect range livestock production in this region, and is the focus of the forage production model developed in Section 2.

2.1.2 Forage Quality

Models for the effects of climate change on forage quality in California also do not yet exist. For ecoregions with a continental climate, Craine et al. (2010) showed that two measures of forage quality—crude protein (CP) and digestible organic matter (DOM)—declined with increasing temperature and increased with increasing precipitation, both reaching maximums in April through June. However, these forage quality patterns did not hold for California and Southwest ecoregions. They found higher than expected CP for California, and that CP actually increased with temperature in this region.

This difference is likely due to the precipitation patterns in Mediterranean climates like California being reversed from that of the rest of the nation; the growing season begins with the onset of rains in the fall rather than the spring in this region. As a result, flowering occurs earlier in California than in the Midwest and Eastern United States, and flowering is usually when CP and DOM start to decline (George and Bell 2001).Indeed, the timing of maximum CP levels was also dramatically different for California, occurring up to 60 days earlier in California than the nationwide mean (Craine et al. 2010). This suggests that methods used to describe the seasonal course of CP and DOM through the year for their broader model may not appropriately characterize conditions in California. Warming may not reduce CP at its peak in California, since this peak occurs in the winter or early spring, but shifts in precipitation patterns could change the timing or duration of the availability of high-quality forage in Bay Area rangelands. Forage quality is generally adequate throughout the late fall to early spring growing season, but by summer the herbage remaining on the range is of such little nutritional value that supplementation of livestock feed is common practice (Van Dyne and Heady 1965). This "forage season," the time during which forage is of high enough quality to meet livestock nutritional needs, could shift or shrink, according to precipitation patterns. To explore the effects of climate change on forage quality, the length of the high-quality forage season is modeled using projected precipitation under future climate scenarios, as described in Section 2.

Subtler effects of climate change on forage quality will likely be mediated at the community and plant levels. Finer-scale models created specifically for California's unique rangeland phenology are needed to better understand the influence of global change on forage quality in Bay Area rangelands. Unlike most rangelands in the world, California's Mediterranean-type rangelands (including those in the Bay Area) are dominated by annual grasses and forbs. Thus, species composition can change seasonally and annually in response to the timing and amount of precipitation and changes in temperature (Young and Evans 1989). Climate change could alter the competitive environment by changing the timing and rates of germination and subsequent vegetative and reproductive development, and these potentially rapid shifts in species composition will influence rangeland forage quality. For example, if forbs increase in abundance relative to grasses, as has been shown to be the case with increasing temperature and precipitation in one experimental California grassland (Zavaleta et al. 2003a), composite CP and DOM can be expected to increase (George et al. 2001b). Later or wetter springs could facilitate woody invasion by trees and shrubs (Dukes and Shaw 2007), reducing both forage quality and quantity. Longer midwinter droughts could paradoxically extend the availability of high-quality forage, since these dry periods during the growing season favor perennials over annuals, and perennials remain green longer, thanks to their more extensive root systems (Corbin et al. 2007).

The elevated level of carbon dioxide (CO_2) in our atmosphere has additional implications for forage nutrition, irrespective of climate change. The Intergovernmental Panel on Climate Change (IPCC) (2007) assessment reviewed these impacts, concluding that nutritional content of forage will decline with increases in CO_2, both because of higher carbon-to-nitrogen ratios in the plants themselves and an increase in dominance of unpalatable grassland species. In the context of California grasslands specifically, Dukes et al. (2011) found that under elevated CO_2 conditions (an additional 300 parts per million [ppm] of CO_2) the invasive and noxious yellow starthistle (*Centaurea solstitaialis*) grows more than six times larger than under ambient conditions, far outcompeting surrounding grasses and forbs. Yellow starthistle is a thirsty weed, and its heavy demand for soil moisture means both that it drives down water availability for other species and that it benefits disproportionately from late rains (Dukes and Shaw 2007). Management of yellow starthistle is already difficult, and it appears that global change will further tip the scales in its favor. If the prevalence of this noxious weed in California grasslands were dramatically increased under future conditions, as the Dukes et al. (2011) suggest, forage quality would be greatly reduced.

These are also other mechanisms by which forage quality could either increase or decrease with global change. Nitrogen deposition and altered fire regimes could further impact species mixes beyond the effects of CO_2, temperature, and precipitation. Many of these factors could interact or feedback on each other, making it difficult to use historical data to forecast future trends. Therefore, models to forecast nutritional quality of rangelands may need to draw on mechanistic relationships established in experimental settings (e.g., Zavaleta et al. 2003a; Dukes et al. 2011).

2.1.3 Animal Productivity

Animal performance is influenced by the thermal environment, primarily through the net effects of energy exchange between animals and surroundings (Hahn 1985). The National Research Council on Beef Production gauges the average thermal neutral zone for beef cattle to be between 15°C–25°C (59°F to 77°F) (Buchanan-Smith et al. 1996). When temperatures exceed this thermal neutral zone, animals suffer heat stress, which can result in dramatic declines in milk production and animal weight gain (Klinedinst et al. 1993; Wolfe et al. 2008; Mader et al. 2009). Most heat stress studies have been on beef and dairy cattle in feedlots, but much of what has been learned in these studies applies to range livestock as well.

Heat stress may play less of a role in grazing systems than in confined animal feeding operations, since the natural air circulation experienced by free-roaming animals prevents temperatures reaching as extreme levels as found in confined operations. However, temperature has still been shown to influence grazing animal behavior. Animals graze less when temperatures exceed the thermal neutral zone, and stop grazing entirely at temperatures above 37°C (99°F); warmer temperatures cause cattle to seek sheltered rest locations during the middle of the day (Harris 2001). Grazing cattle water intake also increases with warmer weather, and if an animal cannot cope with a hot environment (above the thermal neutral zone), daily feed intake will decline to reduce metabolic heat (Hahn 1985). In fact, De Dios and Hahn (1993) showed that a three-day heat wave can decrease feed intake by more than 60 percent. Voluntary feed intake is the main driver of production capacity of livestock; weight gain (and therefore time to slaughter) and/or milk output is directly dependent on the animal's consumption of feed beyond that which is needed to sustain it. Therefore, increasing temperatures, especially in warmer interior regions, could reduce animal performance in rangeland systems, though presumably to a lesser extent than in confined operations.

2.1.4 Pests and Disease

Climate change may also affect pest and disease dynamics in animal production systems, though very little research exists in this field, and none in the context of California. In general, it is thought that endemic livestock pathogens (for example, anthrax, liver fluke, and fecal-oral pathogens) will increase with increased flooding, especially after longer dry periods, while exotic livestock diseases will undergo range extensions and/or more easily locate invertebrate vectors through longer seasons and warmer winters under climate change conditions (Gale et al. 2009). For Great Britain, van Dijk et al. (2010) documented increases in infection rates, longer transmission seasons, and range extensions in several species of helminth (roundworms and flatworms) parasites, coinciding with increases in temperature. However, they maintained that it is still unclear which aspects of temperature (minimum, maximum, mean, or variability) best describe the effects on parasites, and as such, quantifying the effects of climate change on parasites will remain a challenge until more data are gathered.

2.2 Effects of Climate Change on Wine Grapes

Climate change can impact wine grapes through effects on both quantity (yields) and quality, and both aspects have been examined carefully in the literature. There are also expected to be repercussions to pest and disease dynamics in wine grapes in an altered climate, and though many studies have recognized this potential, few have truly integrated it into their assessments. On the whole, wine grape quality appears to be more sensitive to climate change than yields, and greater problems with pests and disease can be expected under future climate conditions.

2.2.1 Yield

Historical climate and yield records show that up until now, warming has mainly benefited wine grapes. Wine grape yields increased from 34 percent in Napa and Sonoma Counties between 1963 and 1996, despite a warming of 1.13°C (2.03°F) over that period (Nemani et al. 2001). Though this is presumably due at least in part to technical progress, Nemani et al. argue that increases in spring minimum temperatures and decreases in summer vapor pressure deficits account for 56 percent of the upward trend in yields. These specific climate variables drive yield increases to a much greater extent than average temperature increases. Other statistical models provide further support to the hypothesis that grape yields increase with spring nighttime temperatures in April (Lobell et al. 2007). In particular, large yield increases were seen with warming above the coldest April temperatures because warmer minimum temperatures mean decreased risk of frost damage during the most vulnerable growing period when frosts can damage the rapidly developing berry clusters and therefore seriously reduce yields.

Despite these trends, unmitigated growth should not be expected for wine grape yields in the Bay Area under climate change conditions. California is already within 1°C (1.8°F) of the optimum April nighttime temperature for wine grape yields; temperatures reaching above this are expected to lead to leveling off and then declining yields (Lobell et al. 2007). Updated yield models using county-level climate data were less reliable than models using state-level data (Lobell and Field 2009), leading to the conclusion that statewide average yields would not be dramatically affected by warming. Furthermore, an even greater concern than overall yields may be that the areas most suited to wine grape production are forecast to shift with climate change.

Lobell et al. (2006) showed that the areas capable of supporting high-yielding wine grape production in California would actually increase with a 2°C (3.6°F) increase in average temperature, which is on the lower end of the expected warming for most Bay Area counties (Figure 1). However, in that scenario, the most suitable counties for growing wine grapes would shift westward along the coast, overlapping with 77 percent of counties currently in production. With a 4°C (7.2°F) average temperature increase, only 33 percent of currently planted vineyards are in regions that would become most suitable to favorable wine grape yields. Warming of this magnitude could create substantial changes from current planting styles and areas. This model is applied in Section 2 with downscaled climate data for the Bay Area to further probe these trends at a finer scale.

2.2.2 Quality

Several climate-related factors are generally associated with high-quality wines: first, mild winters with a low risk of frost damage; second, warm springs that lead to early and even budburst and flowering; and third; low summer temperature variability that allows for optimal maturation (Gladstones 1992). Wine quality ratings on a 0–100 scale increased by 7.5 points in California between 1963 and 1996 (Nemani et al. 2001). While this analysis did not control for non-climate factors that may have changed during this time period, such as grade inflation in scoring, Nemani et al. (2001) found the decline in frosts during winter months accounted for 41 percent of the variation in wine ratings.

As previously noted for wine grape yields, the bulk of the benefit from warming in reducing frost damage has already been accrued. Future warming is expected to result in less-favorable conditions for producing high-quality wines. Models based on growing degree-days (GDD) suggest that average ripening will occur up to 1–2 months earlier in California, and at higher temperatures (Hayhoe et al. 2004). Regions with lower GDD (in the range of 1,000–1,500) generally produce the best dry table wines with light to medium body and good balance (White et al. 2006). Higher GDD and earlier ripening under climate change conditions is expected to lead to degraded quality for all but the cool coastal wine-producing regions of California (Hayhoe et al. 2004). This model is further refined in Section 2 with downscaled climate data to map out the conditions capable of producing the highest-quality wine in the Bay Area and where and when those conditions will shift.

2.2.3 Pest/Disease

Climate change has serious implications for the spread of agriculturally important diseases. Humidity levels in Napa and Sonoma Counties are currently considered optimal for wine production (Gladstones 1992), but projected climate changes will shift premium wine grape production to high humidity/precipitation regions (White et al. 2006). High humidity is associated with higher risk of many disease-related factors that can reduce wine grape quality, such as rot (Pardo et al. 2005) and powdery mildew (Carroll and Wilcox 2003), while increased precipitation increases fungal dispersal through the impact of raindrops on leaves (Willocquet et al. 1998).

Increasing temperatures may also increase pest problems, including vector-borne disease and pest outbreaks. Pierce's disease, caused by the bacterium *Xylella fastidiosa* and transmitted by various species of sharpshooter (*Cicadellidae* family), is limited in its distribution by frost. Cool temperatures (in the range of 7.8°C–13.2°C, or 46.0°F–55.8°F) cause early mortality in the insect vectors of Pierce's disease (Son et al. 2009), and transmission of the disease increases with temperature (Daugherty et al. 2009). Warming throughout the year may therefore accelerate the spread of Pierce's disease, though this effect has not yet been modeled. Occurrence of Pierce's disease has been increasing in Napa and Sonoma Counties, as frost events decline with winter warming (Nemani et al. 2001). Physiologically based demographic models suggest an increase of 3°C (5.4°F) in average daily temperatures would enable the vectors to spread into Napa and Sonoma at the rate currently experienced in Southern California (Gutierrez et al. 2011).

Another important economic pest of wine grapes, the vine mealy bug *Planococcus ficus*, is also thought to be favored under climate change conditions, especially in comparison to its natural enemies. With increases of 2°C and 3°C (3.6°F and 5.4°F) in average daily temperatures, the areas favorable for mealy bug development are projected to shift increasingly northward, meaning more pest pressure in the Bay Area region (Gutierrez et al. 2008). Increasing temperature is also expected to increase the prevalence of the downy mildew *Plasmopara viticola*, making fungicide treatments or other management of this pathogen a greater concern under future climate conditions (Salinari et al. 2006).

The available evidence suggests that the remaining high-yield and high-quality wine-producing areas in the Bay Area will require more attention to disease and pest control. Climate change may therefore require increased investment in pest management and/or disease-resistant rootstock. Research is still needed to quantify potential climate impacts on grape pests and disease.

Section 3: Bay Area Analysis

3.1 Methods

3.1.1 Climate Models

Climate data were acquired from Cayan et al. (2012), downscaled from global climate models using a Bias Corrected Constructed Analogues (BCCA) technique to produce two climate scenarios: the lower-emissions B1 scenario and the higher-emissions A2 scenario. Four climate models output the daily temperature and precipitation projections required by the rangeland and wine production models: Centre National Recherche Météorologique (CNRM) CM3, Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1, National Center for Atmospheric Research (NCAR) CCSM3.0, and NCAR PCM1. The wine and rangeland production models were run for all eight model/scenario combinations for each of the 244 12 x 12 kilometer (km) grid cells that comprise the Bay Area region.

3.1.2 Forage Production

Strong relationships have been documented between forage production and accumulated degree-days during the growing season (George et al. 1988), accounting for 75 to 95 percent of the variation in the data. Based on field data and expert experience, the forage production season begins after the first week in which precipitation exceeds 25 millimeters (mm) (George et al. 1988). This is known as the “germinating rain.” The end of the growing season was not forecast in the George et al. (1988) research, but rather was based on field calculations that measured biomass until annual grasses were between the soft and hard dough stage of seed maturity. Expert opinion suggests that a simple water balance model could approximate the end of the season, since plants will begin to senesce when water loss exceeds water gain (George, personal communication). Some work has indicated that phenology may be relatively fixed in annuals, with late watering treatments only delaying senescence by a week (Jackson and Roy 1986). However, field data obtained from the University of California Sierra Foothill Research and Extension Center that recorded the date of peak standing crop (forage) showed that this peak forage date does vary from year to year, by up to a month. Therefore, a model to simulate the season-end was trained on this data set, along with California Irrigation Management Information System (CIMIS) weather data for precipitation and evapotranspiration. Calculating the point at which cumulative evapotranspiration exceeded cumulative precipitation over a moving window of 60 days best predicted peak forage date. Including other pathways for water loss (notably run-off or drainage) may provide a more realistic model for estimating peak forage date, but in absence of such data, this simple model generally came within two weeks of actual peak forage date.

While forage, defined as the standing herbage used in grazing, is available year-round in California, the dead material consumed outside of the forage growing season is much lower in quality and cannot meet nutritional needs without supplement (as noted in Section 1). There are some annual forbs that bloom in summer, but these species do not make up a substantial proportion of grassland production (Chiariello 1989). Therefore the growing season during which high-quality forage is produced (hereafter “forage season”) will be considered as an important component of forage production (determining availability, described below). Degree-days were calculated for each day throughout the forage season via a sine function using minimum and maximum daily temperatures above a base temperature of 5°C (41°F) (according to Logan and Boyland 1983). Accumulated degree-days (ADD) were taken at monthly timesteps, beginning with germination, and the final timestep, including all degree-days past the end of May if the forage season went beyond that (which it rarely did). Accumulated degree-days was then used to calculate forage production with the regression equations in Table 3, reproduced from George et al. (1988).

Table 3. Relationship between Forage Production and ADD, Reproduced from George et al. (1988)

Sample Area	Forage production ~ ADD	R^2
1	y = 120 + 5.2x	0.95
2	y = 14 + 4.4x	0.91
3	y = -90 + 3.8x	0.85
4	y = -141 + 3.1x	0.82
5	y = -54 + 3.9x	0.77
6	y = -280 + 4.9x	0.88
7	y = 77 + 2.2x	0.74
8	y = 138 + 2.8x	0.76
9	y = 96 + 4.1x	0.91
10	y = 82 + 2.7x	0.74

Absolute forage production obviously varies depending on the chosen equation, but as the relationship is linear, relative measures such as the change in forage production over time were very consistent, differing by only 2 to 3 percent. For this reason, future values for peak forage production are presented in terms of change from historic values.

Growth curves were constructed using the forage production estimates from each timestep, and again it is the relative measures, such as the shape of the curves and the differences between them, that are worth examining, rather than the absolute numbers. These growth curves help to determine which parts of the season have the greatest differences between historical and future scenarios, and thus hint at the mechanisms behind the difference. Differences in the first time step may indicate that germination date is an important factor. Steeper slopes throughout the middle of the curve would point to the role played by warmer winter and/or spring temperatures. Differences in the slope leading up to the final time step could be at least partially explained by differences in season end date and the length of time for degree days to accumulate in that final period.

Two additional considerations in the effects of climate on forage production are reliability and availability. Forage availability is measured by the length of the "forage season," from germination to senescence; the period over which livestock can be productively grazing the land because high-quality forage is available. A close inspection of how season length varied over time revealed that in certain years for certain grid cells, the growing season never occurred. In those years for those areas, precipitation never exceeded 25 mm over the span of one week. In terms of estimating forage production, those years are assigned a value of 0, but the frequency of occurrence of such events is also the focus of a separate analysis on the reliability of forage production.

Results are presented on maps of rangeland habitats, defined by Heady and Child (1994) as any of the following biomes: savannah; grasslands, including meadows or herbaceous habitats; and shrublands, including scrub and chaparral. These biomes were selected from the Existing Vegetation Types layer of the national LANDFIRE dataset (USGS 2006) and overlaid on the climate models. Not all rangeland habitats are necessarily actively grazed, but no comprehensive map of grazing lands exists for the Bay Area. Most of the "pasture" acreage in Table 2 is actually rangeland used for grazing, with the exception of Solano County. Irrigated pastures comprise the bulk of Solano's pasture acreage, found predominantly in the eastern half of the county. Irrigated pastures were not included in the rangeland maps because they will not respond to changes in precipitation patterns in the same way and because they are often rotated against row crops, making it difficult to map them over long timescales.

3.1.3 Wine Grape Production

Previous work in California has culminated in models assessing climate ramifications to wine yields and quality, primarily at the state scale (Lobell et al. 2006, 2007; Lobell and Field 2009) but more recently at the vineyard scale(Nicholas et al. 2011). Much can be learned by incorporating the substantial spatial heterogeneity of the Bay Area into a finer-scale model.

Lobell and colleagues (2006, 2007) analyzed historical wine yields and climate patterns and found the dominant variables predicting yields to be monthly means for minimum temperature in April ($T_{n,4}$), precipitation in June (P_6), and precipitation in the September of the previous harvest year (P_{-9}). After first removing a linear trend of increasing yields due to technology (9.4 percent over a 24-year period, or roughly 0.4 percent per year), the Lobell model represented wine yield anomalies (the variation in wine yields due to climate) by the following equation, accounting for 66 percent of the variance:

$$Y = 2.65T_{n,4} - 0.17T^2_{n,4} + 4.78P_6 - 4.93P^2_6 - 2.24P_{-9} + 1.54P^2_{-9} – 10.50$$

Wine yield anomalies were thus computed for the Bay Area grid, in tons-per-acre difference from statewide averages from 1980–2003. It is not meaningful in this case to compare future to historic absolute measures, because they are essentially different units, anomalies of different base yields (increasing independently through time). For instance, if the model predicted an anomaly of a 10 percent increase for a particular place in the year 2020 and a 10 percent decrease in 2090, the yields would still be higher in the future because the overall yield trend (0.4 percent per year due to technology) increased more than the anomalies during that time. In order to more easily compare different time periods, the anomalies were added back to the overall trend to produce an estimate of total yield. Future yield was then divided by historic yield to calculate percent change in wine yields over time, and the base trend again was removed to determine the change in yields due to climate.

Potential impacts of climate on wine grape quality are indicated by mean temperature during the month of wine ripening. Hayhoe et al. (2004) designated ripening-month conditions as optimal (15°C–22°C, or 59°F–72°F), marginal (22°C–24°C, or 72°F–75°F), or impaired (above 24°C, or 75°F) for producing high-quality wine grapes, based on thresholds established by Gladstones (1992) to balance sugar accumulation and acid declines. Marginal conditions can still produce high-quality wines, but may do so less consistently, while impaired conditions are unlikely to produce high-quality table wines. This approach estimated that grape ripening requires 1,150–1,300 degree-days above 10°C (50°F) between April and October (Hayhoe et al. 2004). This model uses a simpler degree-day calculation than the forage model:

$$DD = (T + t)/2 - g,$$

with T and t as daily maximum and minimum temperatures respectively, and g as the base temperature (in this case 10°C, or 50°F). Degree-days were accumulated starting April 1 and "ripening date" was set as the day ADD exceeded 1,150. The following 30 days were set as the "ripening month," during which 1,300 degree-days were exceeded as well. The mean temperature during that ripening month was calculated for categorization into optimal, marginal, or impaired wine-growing conditions.

As with the forage production and rangeland maps, results for wine production are displayed on maps generated from the LANDFIRE dataset for agricultural habitats. The mean percent change in wine yields was calculated for all grid cells containing agricultural habitat in each county that grows wine grapes, even though not all agricultural habitat produces wine grapes (Table 2 provides a sense of this for each county). It is not possible to differentiate between wine grapes and other crops because current agricultural commodity data are limited to the county level, and in any case, wine grape production in the future is not necessarily limited to where it is presently produced. A semi-transparent background of the rest of the county is also included in these maps, because wine grapes are a high-value crop, and other land uses besides agriculture could conceivably be converted to grow wine if the conditions were right. Indeed, vineyard conversion is one of the biggest threats to rangeland preservation in the Bay Area (Marty 2012).

3.2 Results

3.2.1 Forage Production

Increases in forage production generally can be expected in future climate conditions throughout rangelands of the Bay Area. The four different model outputs for the A2 emissions scenario show little difference between early-century (2005–2034) and mid-century (2035–2064) projections, with increases in peak forage production of 10 to 15 percent compared to historical (1961–1990) conditions (Appendix A, Table A-1). By late-century (2070–2099), the increases more than double: 26 to 32 percent higher forage production across eight Bay Area counties. Early-century model outputs for the B1 scenario are indistinguishable from the A2 scenario, and the B1 scenario then follows a more gradually increasing trajectory than the A2, with greater increases than the A2 for mid-century and lesser increases than the A2 for late-century (Appendix A, Table A-2). The variability between the different models is also greater for the B1 scenario, especially by late-century, with confidence intervals several times as wide as those in A2.

Figure 2 provides a sense of the spatial heterogeneity of climate impacts at a finer scale. Future climate change could result in late-century increases in peak forage production of up to 40 percent for the higher-emissions A2 scenario in much of Napa, southern Marin, and northern Sonoma Counties, though these same areas show more modest increases of 20 to 25 percent in the B1 scenario. Northeastern Santa Clara County, in contrast, shows increases above 30 percent for both emissions scenarios.

Figure 3 plots monthly production over the forage season for different regions in the Bay Area, showing that differences between historical and future production are apparent even early in the forage season, and accumulate over the course of the season.

Figure 4 further highlights these differences, plotting the derivative of this production curve, the increase from historical to A2 or B1 late-century production at each timestep. In general, production in the North Bay (Marin/Sonoma and Napa/Solano) is consistently higher in the A2 scenario than the B1 scenario, while in the South Bay (Alameda and Santa Clara) the results are more mixed. These differences are also more spatially heterogeneous in the South Bay. In Alameda and Santa Clara, regional differences even within a county can exceed the differences expected from climate change; the highest-producing regions have higher production in the historical periods than some of the lower-producing regions, even in the future (Figure 3).

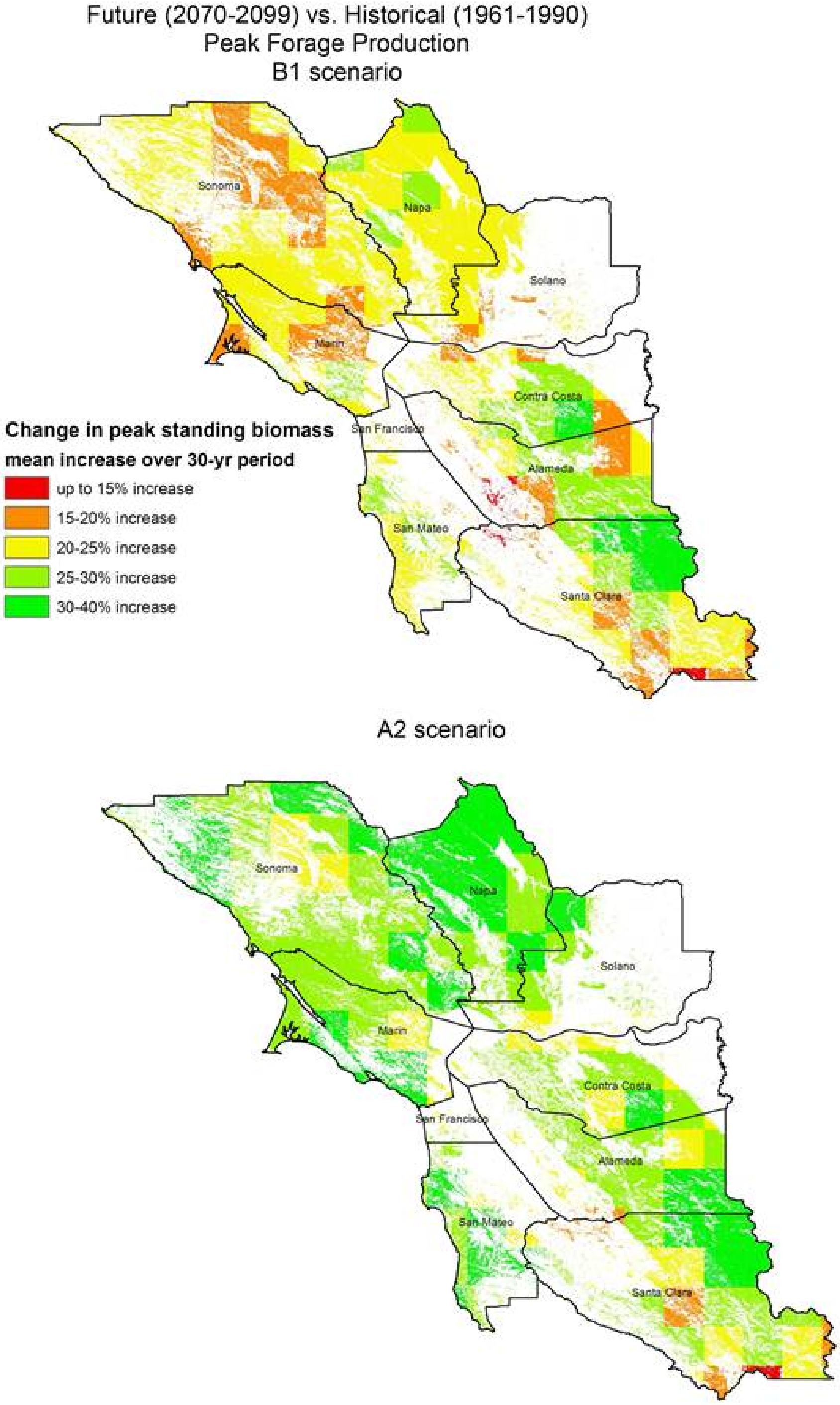


Figure 2. Change in Peak Forage Production by Late-century (2070–2099), Relative to Historical Conditions (1961–1990), Shown for Current Rangeland Habitats (Grassland, Savannah, and Shrubland) in the Bay Area

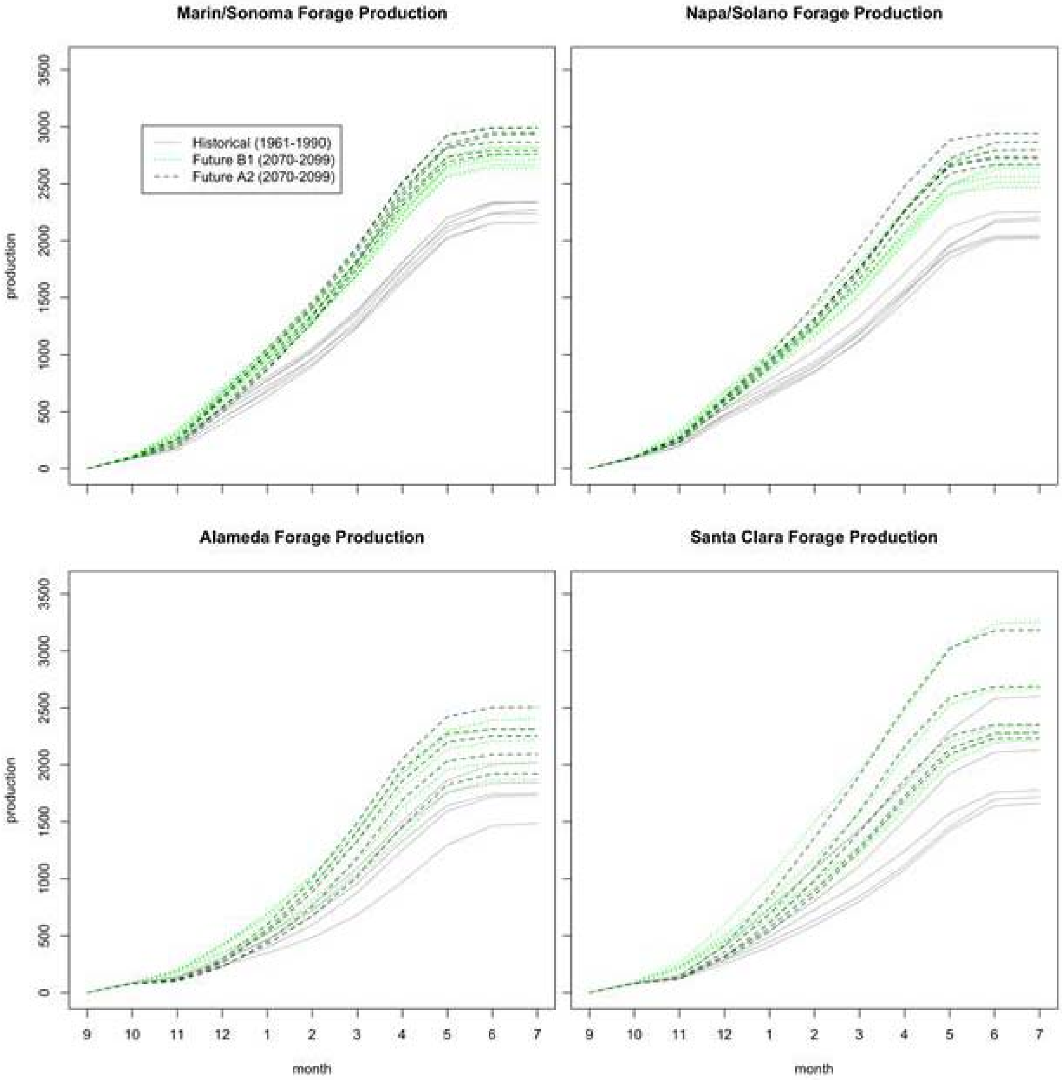


Figure 3. Seasonal Growth Curves for Forage Production in Different Regions Under Historical (1961–1990) and Future (2070–2099) Climate Conditions. Multiple lines of the same color represent different 12 x 12 km grid cells in the region. Only cells containing rangeland habitat were used (see Figure 2).

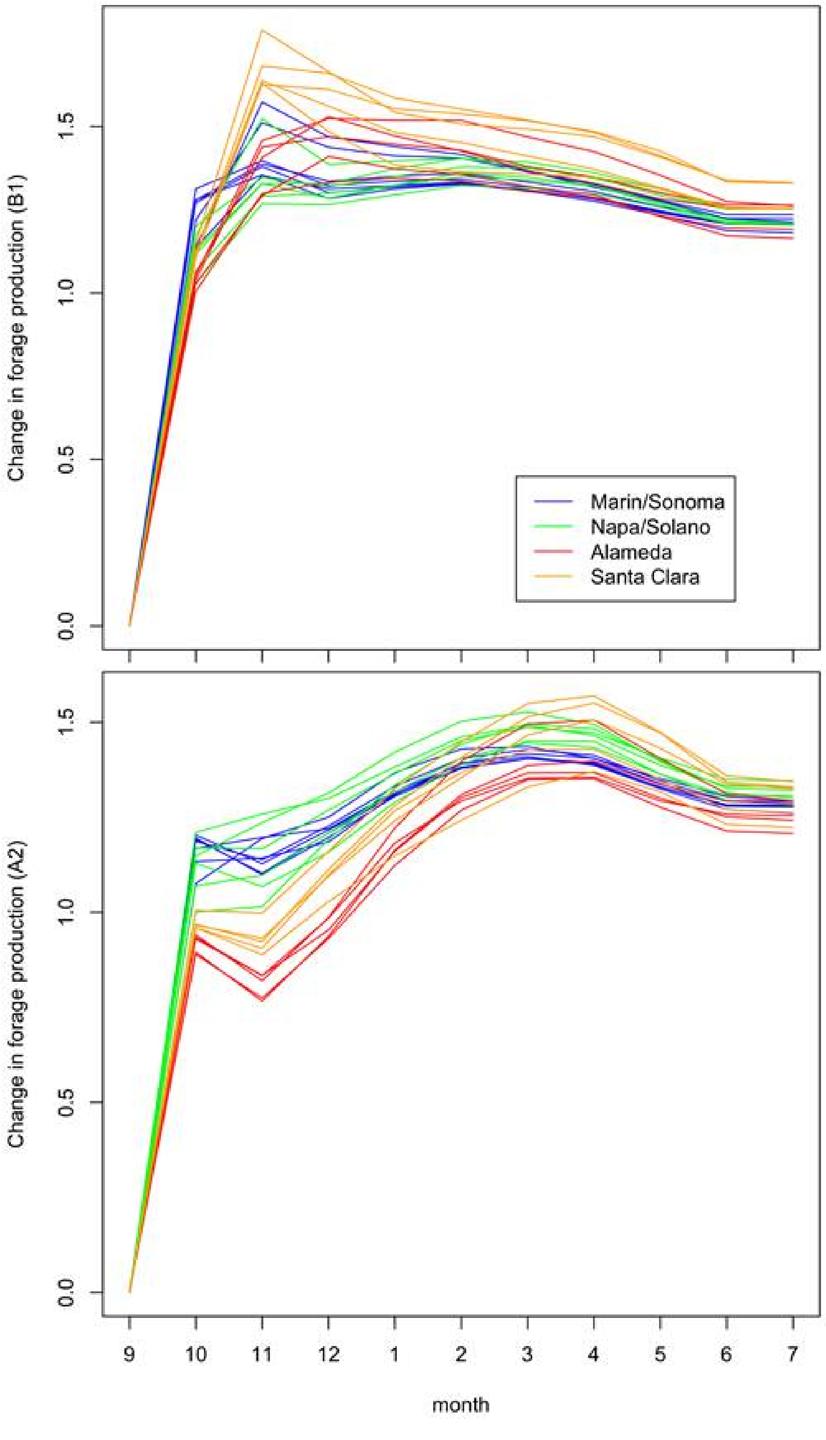
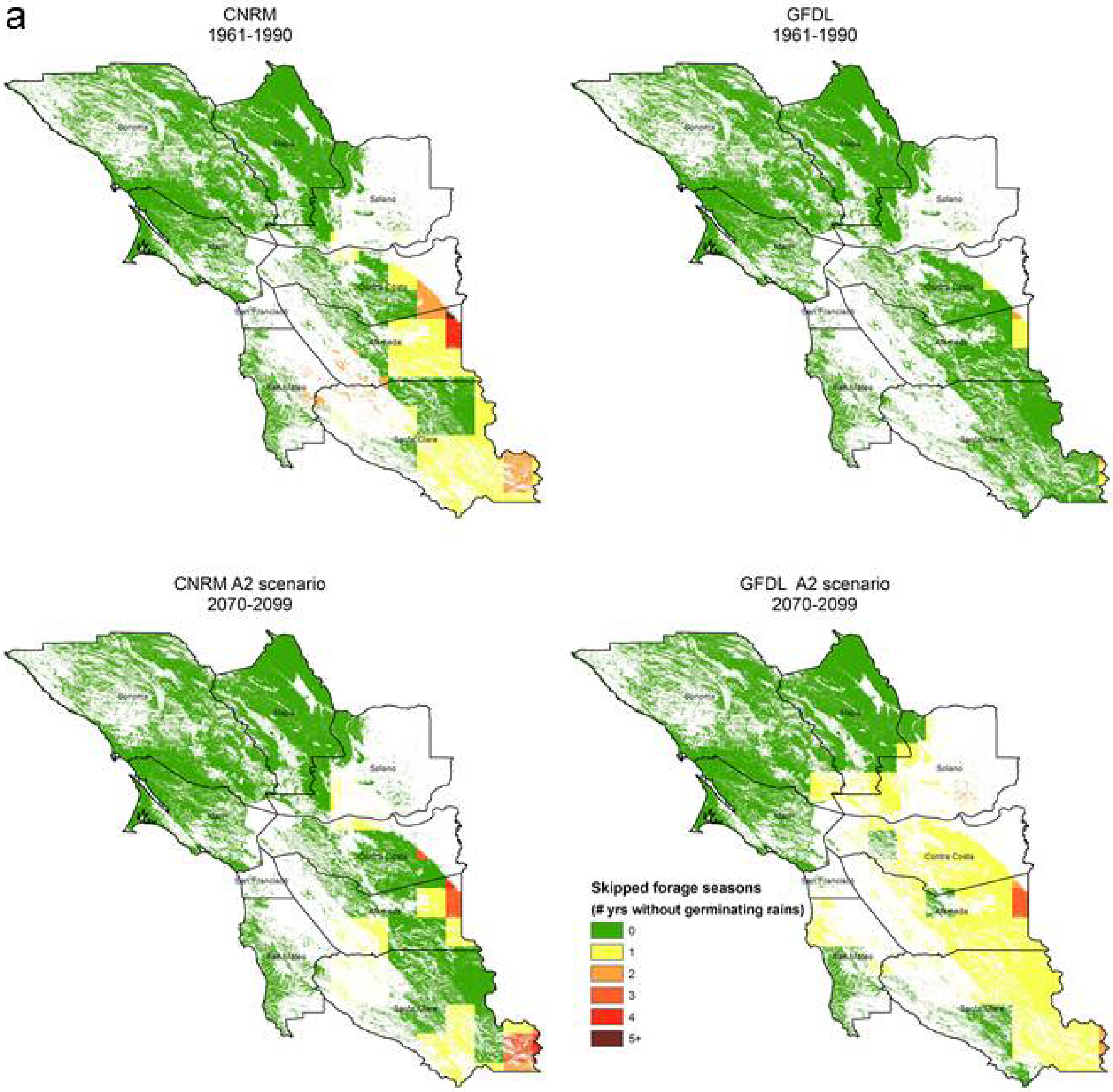


Figure 4. Change in Forage Production from Historical (1961–1990) to Future (2070–2099) Climate Scenarios. As in Figure 3, multiple lines of the same color represent different grid cells of rangeland in that area.

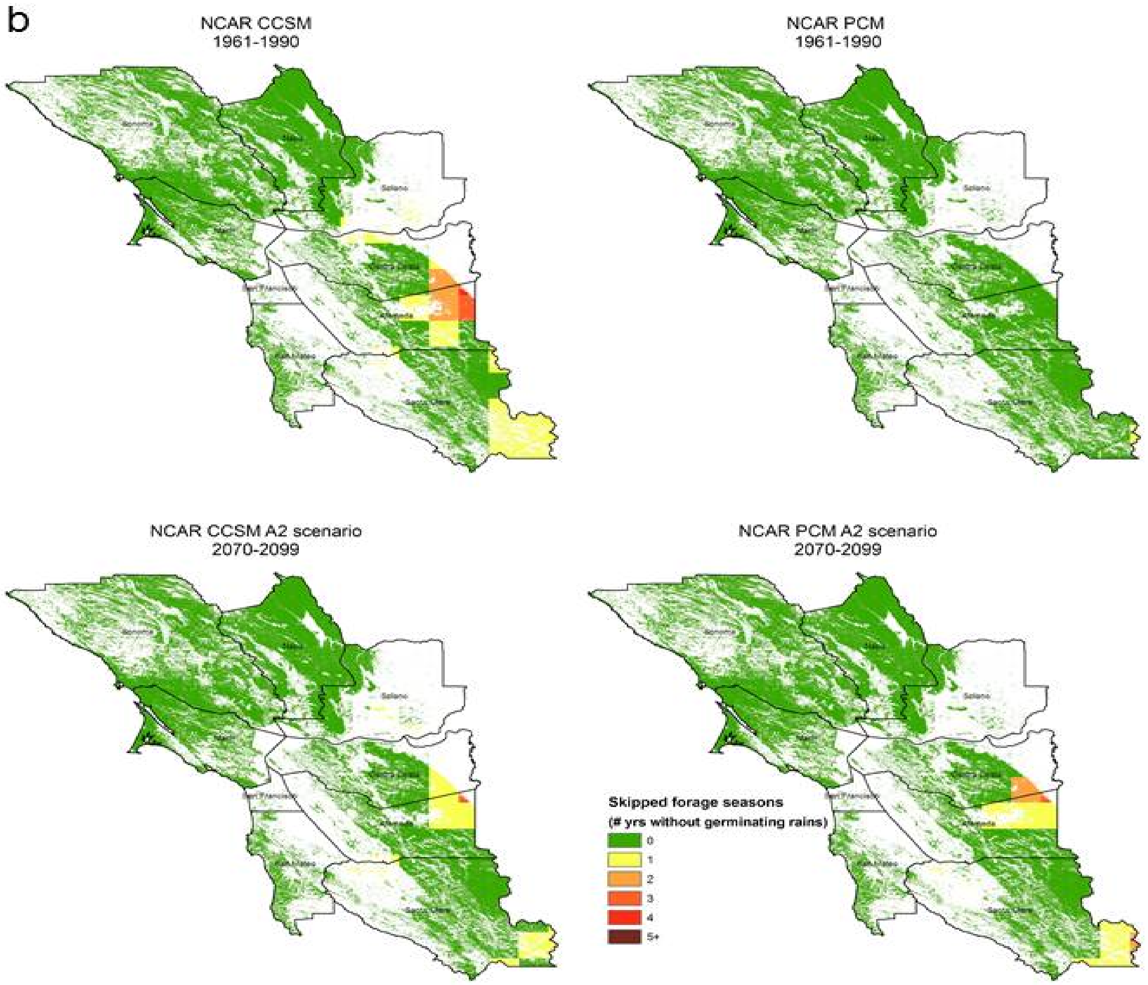
While helpful in detecting broad trends, viewing forage production over 30-year time periods hides the effect of extreme events. This model revealed years in which the germinating rain never occurred, and the growing season was essentially skipped. The models suggest that Alameda, Contra Costa, and Santa Clara counties were historically affected by these extreme dry years, experiencing one or two such events (or as many as four in the CNRM model for Alameda) over the 30-year period (Figures 5a and b).

The difference between historic and future conditions is highly model-dependent, with the GFDL model (Figure 5a) suggesting an increase in skipped seasons across most of the southern counties, while the NCAR CCSM model(Figure 5b) suggests a decrease in such events and a much smaller affected area. In fact, there is more variation between the four models than between the different time periods (Appendix B). The two emissions scenarios also produce vastly different results, as depicted in Figure 5c, which maps the four-model mean change in frequency of skipped seasons across the Bay Area. The mean of the models suggests a lower chance, on average, of skipped seasons in the southern counties for the B1 scenario compared to historic conditions, and a higher chance for the A2 scenario. The only outcomes that all models support are that the North Bay is almost entirely unaffected in all time periods, and southeastern Santa Clara experiences more extreme dry years under future conditions, meaning lower reliability of forage.

Forage availability is projected to be reduced by climate change, as the "forage season" or length of time during which high-quality forage is produced appears to grow shorter under both emissions scenarios, though markedly so only under the A2 scenario (Figure 6).The A2 scenario suggests that two-week shorter seasons can be expected by late-century for much of the Bay Area, with Santa Clara's seasons shrinking by more than three weeks (Appendix C, Table C-1). Rangelands in Marin and Napa fall on the lower end of that range, exacerbating historical differences between the Northern and Southern Bay area. Future forage season in eastern Santa Clara and Alameda Counties could drop as low as 100 days in length, a full 50 days shorter than the shortest season found in Marin or Sonoma Counties (Figure 6). The B1 scenario shows modest decreases in season length of a few days to a week, but the differences are not significant (with overlapping 95 percent confidence intervals between historic and late-century, see Appendix C, Table C-2).



Source: Cayan et al.



NCAR CCSM 1961-1990

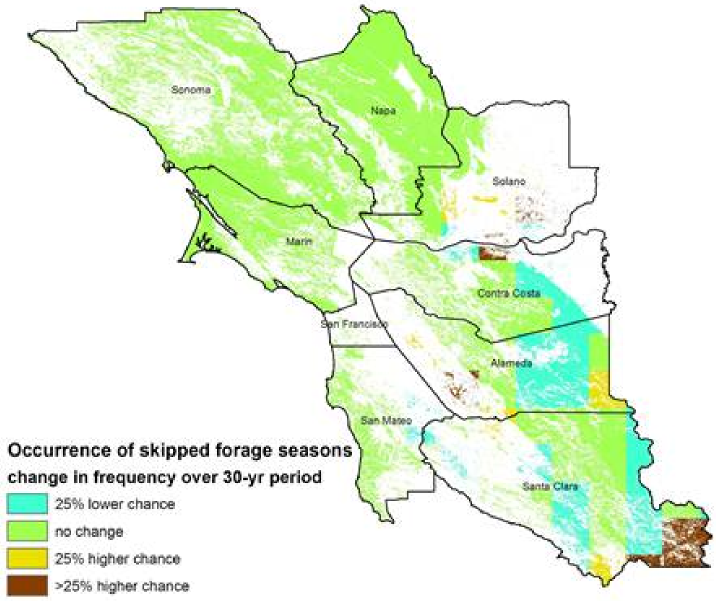
NCAR PCM 1961-1990

NCAR CCSM A2 scenario 2070-2099

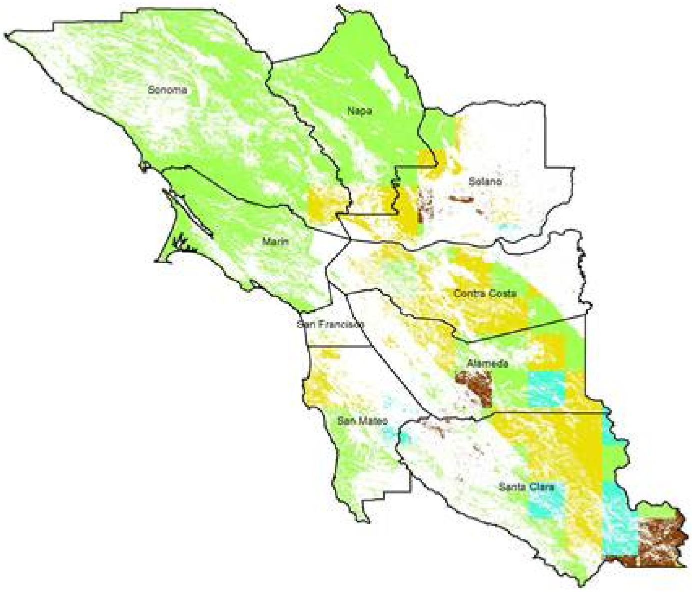
NCAR PCM A2 scenario 2070-2099

Source: Cayan et al.

Figure 5a, b. Total Number of Skipped Forage Seasons in a 30-year Period for Historical (1961–1990 and Future (2070–2099) Conditions, Projected for (a) CNRM and GFDL Models and (b) the NCAR CCSM and PCM Models. The forage season is considered "skipped" if precipitation required for germination (>25 mm over a one-week period) never occurs in a given year.


Future (2070-2099) vs. Historical (1961-1990)
Skipped Forage Seasons
B1 scenario

A2 scenario



Source: Cayan et al.

Figure 5c. Change in the Number of Skipped Forage Seasons in the Future (2070–2099), Compared to Historical (1961–1990) Conditions for Current Rangeland Habitats in the Bay Area. The forage season is considered "skipped" if precipitation required for germination (>25 mm over a one-week period) never occurs in a given year.

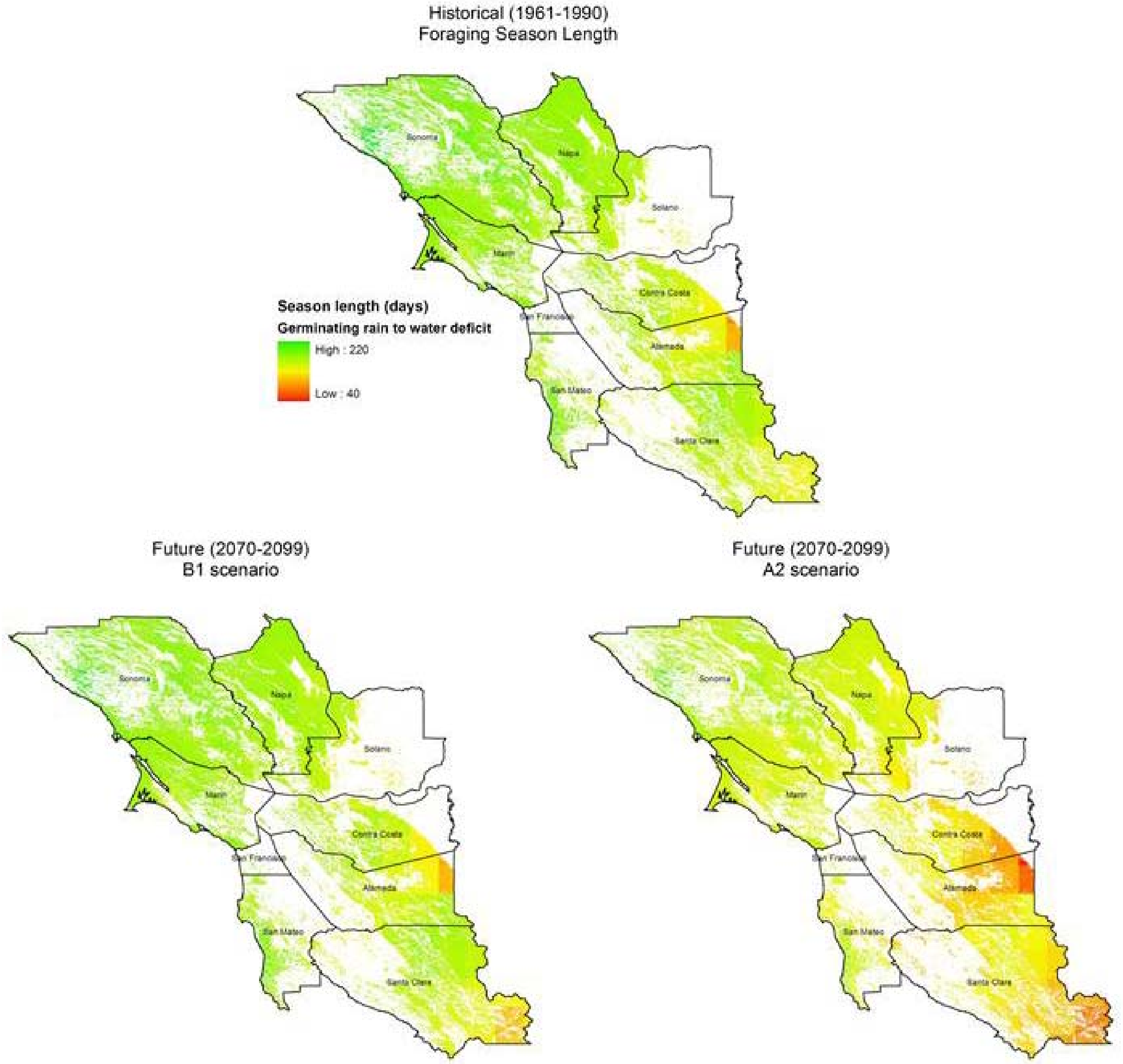


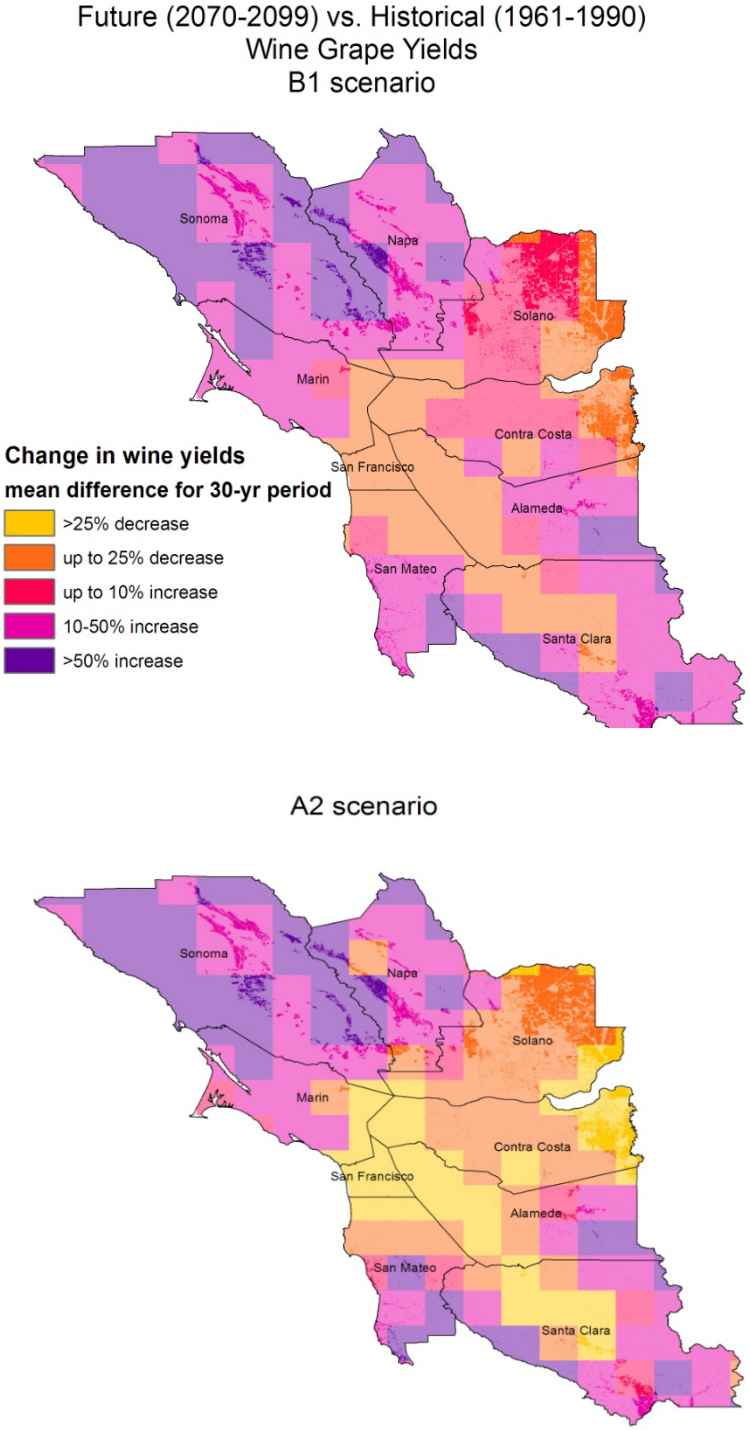
Figure 6. Change in Rangeland Season Length by End-century (2070–2099), Relative to Historical Conditions (1961–1990) for Current Rangeland Habitats in the Bay Area

3.2.2 Wine Grape Production

For wine grape production, differences between climate models are relatively small, and the main difference between the two emissions scenarios is that B1 generally results in higher yields (greater increases or smaller decreases) than A2 (Appendix D). The largest source of variation in wine yield change is spatial. Wine country fares well under both scenarios, with Napa yields increasing 30 to 40 percent by late century and Sonoma yields increasing 50 to 60 percent by late-century. Alameda, not as prominent a wine-producing region but still devoting nearly a third of its non-pasture agricultural acreage to wine, shows similar increases of 35 to 45 percent. Though wine accounts for only a fraction of the agricultural acreage throughout the rest of the Bay Area (Table 2), future climate conditions would decrease yields in the agricultural areas of Contra Costa. Impacts on wine yields in Solano and Santa Clara are variable under different climate models and emissions scenarios, but are not as consistently positive as in wine country. This dichotomy is visible in Figure 7, which shows benefits to wine yields in the North Bay and detriments in the South Bay under future climate conditions.

Wine ripening date, determined by the accumulation of degree-days above 10°C (50°F) reaching 1,150 after April 1, occurs earlier under both emissions scenarios and all climate models (Appendix E). The ripening date moves back steadily over the three time periods, occurring an average of two weeks earlier in the B1 scenario and nearly a month earlier in the A2 scenario (more than a month for some models).

The mean temperature in the month after wine ripening increases in all climate models and emissions scenarios. As described in the methods (following Hayhoe et al. 2004), elevated temperature during ripening month means reduced wine quality if the temperature passes a certain threshold. Historical conditions put most of the Bay Area, wine country in particular, in the "optimal" category for producing high-quality wines, 15°C–22°C (59°F–72°F) (Figure 8). By mid-century in both emissions scenarios, temperatures throughout much of the Bay Area (including Napa) climb into the 22°C–24°C (72°F–75°F) range considered "marginal" for producing high-quality wines (Appendix F). By late-century in the A2 scenario, Sonoma reaches the "marginal" range, while the rest of the Bay Area exceeds the 24°C (75°F) "impaired" threshold above which high-quality wines are rarely produced (Figure 8).


Future (2070-2099) vs. Historical (1961-1990)
Wine Grape Yields
B1 scenario

A2 scenario

Figure 7. Change in Wine Yields Due to Climate (base trend removed) by End-century (2070-2099), Relative to Historical Conditions (1961–1990). Brighter colors (corresponding to legend) show current agricultural acreage in the Bay Area; lighter colors show change in conditions for wine grape growing in areas not currently farmed.

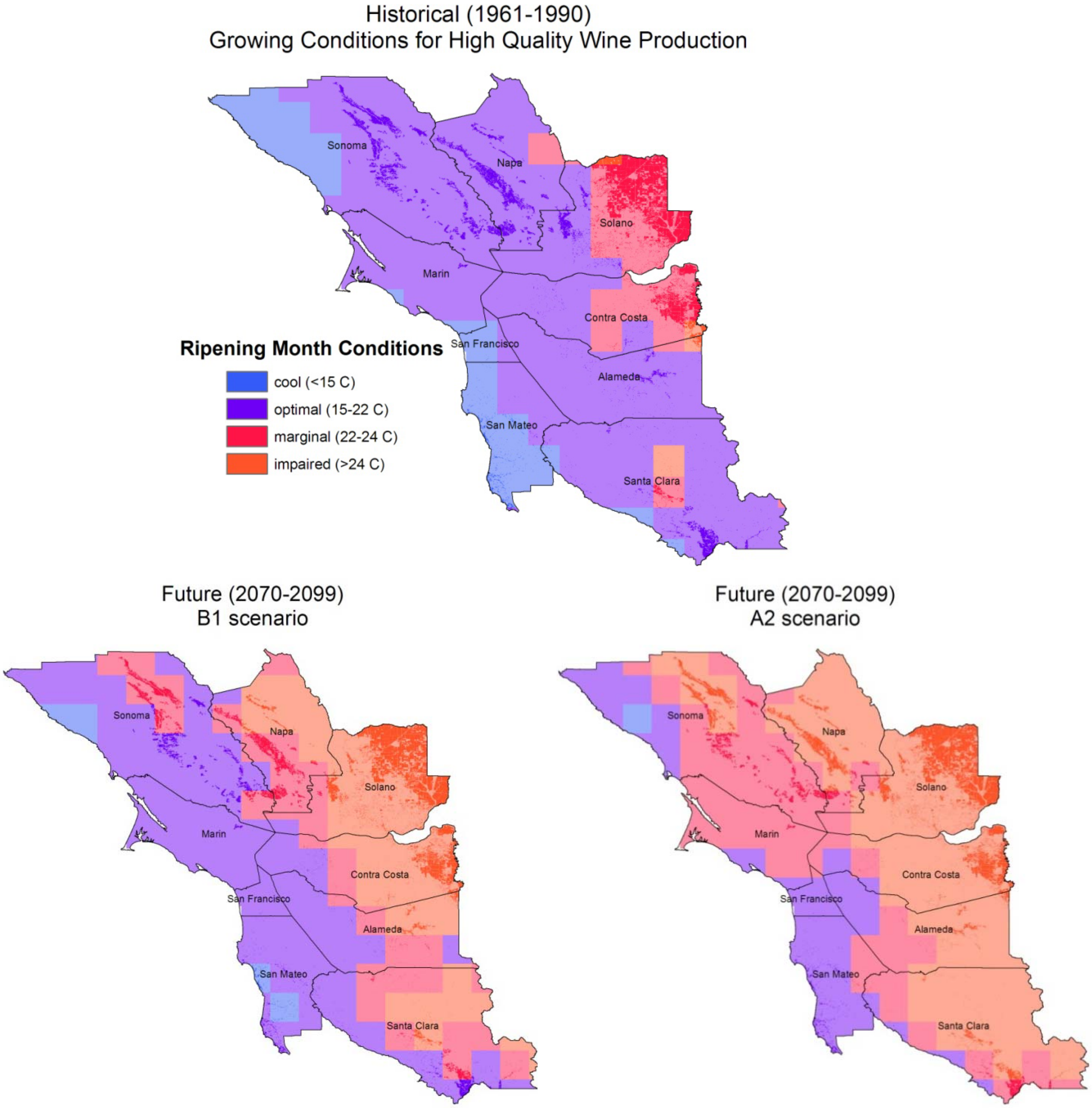


Figure 8. Historical (1961–1990) and Future (2070–2099) Ripening Month Conditions for Wine Grape Growing, Under Two Climate Scenarios (B1 and A2). Average temperatures during ripening month determine whether climate is optimal (15°C–22°C), marginal (22°C–24 °C), or impaired (>24 °C) for producing high-quality wines. Brighter colors (corresponding to legend) show current agricultural acreage in the Bay Area; lighter colors show change in conditions for wine grape growing in areas not currently farmed.

3.3 Discussion

3.3.1 Forage Production

This discussion will further explore the number of ways climate change can affect rangelands, and the consequent implications for management. Future climate effects on the quantity, timing, reliability, and overall availability of forage production were modeled here, while plant and community-level impacts on the nutritional value of the forage and the response of the animals themselves are additional factors that should be considered. At the habitat level, future vegetation and land-use mapping can further inform the implications of climate change for the future of rangeland production. A variety of management strategies could serve as potential adaptation measures to the threats posed by climate change.

The increases in forage production are widespread throughout the Bay Area, and are especially pronounced in northeastern Santa Clara and southern Alameda counties. The shape of the production curves suggests that these gains are driven primarily by winter warming. The shape of the curve at the beginning and end of the forage growing season is more influenced by precipitation, as discussed below regarding forage availability, but the majority of the gains over historical forage production are accrued in winter months. The slopes of the production curves through the winter months are steeper for both future emissions scenarios (Figure 3). Production increases in the A2 scenario reach a maximum in most parts of the Bay Area by the end of February or March (Figure 4). In the B1 scenario, the maximum occurs much earlier, by the end of October or November, but the magnitude of the maximum differences between historic and future production are much more variable than in the A2 scenario (25 to 80 percent increases for B1, 30 to 55 percent for A2).

While grazing may benefit from increases in forage production, both at its peak and throughout the winter, the overall reliability and availability of forage are other serious considerations for ranchers. The frequency of years so dry as to result in a “skipped” forage season is low (only a few times in a 30-year period), and therefore the zeroes for forage production in those few years do not significantly affect the overall 30-year mean, especially when production in an average year is 30 percent higher in the future compared to historic conditions.

Such events do not need to occur frequently to effect ranchers on a year-to-year basis, however. As noted in Section 1, lower reliability of forage can effectively reduce the carrying capacity of the land (Hanson et al. 1993), affecting stocking decisions. Furthermore, even infrequent occurrence of such an extreme event as a missed growing season could be catastrophic for some operations. A year during which no or very little forage is produced could add potentially irrecoverable costs to an enterprise with an already thin profit margin. Nimble operations could move livestock to other wetter (or irrigated) regions, begin irrigating some of their pastures, or purchase supplemental feed, but each of these present additional costs that not all operations will be able to bear. The current projections for precipitation in the Bay Area are highly uncertain and very model-dependent, making it difficult to draw many conclusions regarding drought and the impact of climate change on forage reliability, but this does not diminish the importance of this issue to ranching sustainability. At a minimum, it would be prudent for ranchers to consider their options and make emergency plans for dry years, especially those in southeastern Santa Clara County.

Meanwhile, the higher forage production seen in future scenarios will be packed into a shorter amount of time. The reason availability of high-quality forage is expected to decline in the future is primarily because the growing season will end earlier (by 10–12 days on average); this shift is illustrated by the shallower slope in the growth curves during the month of May in the future as compared to historic conditions (Figure 3), and is consistent in both emissions scenarios and across the Bay Area.

The main differences between scenarios and among different regions are due to the timing of germination. In the A2 scenario, the seasons in Santa Clara and Alameda are delayed by a week to 12 days compared to historical conditions; whereas, the season in the northern Bay Area starts only slightly (2–3 days) later than historically. This intensifies the historical differences between the North and South Bay (with the South Bay germination occurring a week to a month behind the North Bay's). In contrast, earlier rains mean earlier germination (2–3 days on average, up to a week) throughout much of the Bay Area for the B1 scenario, except for southeastern Santa Clara, where germination occurs up to a week later. The earlier season start almost compensates for the earlier end in the B1 scenario, which is why the impact of climate change on season length is much subtler than for the A2 scenario. This also contributes to production in the late-century B1 scenario edging out that in the A2 scenario during the first few months of the season (Figure 3).

Forage availability portrayed in the current model also captures, to a certain extent, seasonal impacts to forage quality. As discussed in Section 1, crude protein content generally exceeds livestock needs for growth and maintenance during the forage-growing season, but outside of this growing season, from late spring and summer through early fall, livestock require protein supplementation to utilize forage even for maintenance (Van Dyne and Heady 1965). Delayed onset of the germinating rains(as seen in the A2 scenario model projections) would delay improvements to forage quality that could affect the traditional fall calving season, while earlier onset of the dry season (as seen in both emissions scenarios) could require early weaning in the cow-calf operations that dominate Bay Area livestock production (Sheila Barry, personal communication).

In general, the decrease in the availability of high-quality forage, based on the growing season length seen with higher emissions, would increase the amount of supplemental feed needed or require other alternatives to gain access to high-quality forage, as discussed above. Additional climate impacts on the nutritional content of the forage, beyond the impacts of seasonality, will also likely play a role in the response of livestock systems to climate change. More data in Californian systems are needed before climate impacts can be forecast for these variables. Qualitatively, however, if the nitrogen content of forage decreases with increased CO_2 (IPCC 2007), or if rangeland plant community composition shifts toward less-palatable species (Dukes et al. 2011), more forage would need to be consumed for the animal to obtain the same amount of protein. Whether this increased demand would exceed the increased supply projected for most years in the future is not currently possible to determine.

Regardless of the balance between future forage quantity and quality, rising temperatures will alter animal performance for ranching operations throughout much of the Bay Area. As average summer temperatures climb past the upper threshold of the thermal neutral zone (25°C, or 77°F) in the eastern and southern Bay Area (Figure 1), cattle will reduce their feed intake, seeking more shelter and rest (Buchanan-Smith et al. 1996; Hahn 1985), and ultimately reducing their weight gain and increasing their time to slaughter. The North Bay will remain within cattle's thermal neutral zone through the end of the century, which may make it an increasingly attractive area for grazing, as the rest of the Bay Area and California at large grow too warm for optimal cattle performance. In reality, many ranching operations in the interior portions of California already shut down production during summer months due to lack of forage, either timing their slaughter accordingly or moving their cattle into wetter alpine areas. A future possibility for adaptation may also be to shift to more heat-tolerant breeds of cattle or even goats or sheep (Seo et al. 2010). Such management strategies will help ease the burden of progressively hotter summers.

Another important consideration for animal performance under future climate conditions in the Bay Area is the availability of livestock water. Dramatic reductions are expected in Sierra snowpack by the end of the century, leading to decreased spring flow in creeks throughout the San Francisco Bay watershed (Knowles and Cayan 2002). Seasonal water sources for livestock will therefore dry up earlier than usual, and water available for stock ponds can also be expected to decline as urban demands need to be met (HRC-GWRI 2011).Without a nearby water source, the ability of livestock to graze will be limited, regardless of forage quality and quantity (Sheila Barry, personal communication).

In addition to climate change impacts at the plant or animal level, vegetation modeling shows that there will be impacts at the habitat level that should be considered. Winter warming is expected to promote transitions from grassland to shrubland, chaparral, or redwood forest throughout much of the North Bay, especially in Pt. Reyes, where coyote brush will dominate (Cornwell et al. 2012). Of course, this model does not take management into account, and grazing itself is a proven way of keeping rangeland grazable (Huntsinger et al. 2007). As long as ranchers continue to work the land consistently, they should be able to keep much of this projected woody encroachment at bay. However, extra vigilance will be required in much of the North Bay to maintain desirable grazing lands, which may add to operating costs, depending on usage. Shrub invasion is already common in Bay Area grasslands when disturbance from grazing or fire is infrequent, and of particular concern to rangeland productivity is the recent invasion of non-native nitrogen-fixing shrubs such as gorse, lupine, French broom, and Scotch broom (Tyler et al. 2007). These invasions are especially hard to manage, as they are insensitive to fire and many other management techniques, and as nitrogen-fixers they alter the soil in ways that can have cascading effects on the whole plant community, facilitating invasion of exotic grasses. (D'Antonio et al. 2007). Meanwhile, the eastern South Bay is projected to shift from Oak woodland and chaparral to grassland, and the Peninsula from Redwood/Douglas fir to chaparral (Cornwell et al. 2012), both of which would open up more land for potential grazing.

Furthermore, wildfires have been projected to increase in area by 40 to 50 percent throughout much of the Bay Area, which could further expand the conversion to grassland in many areas (Lenihan et al. 2006). However, habitat throughout the entire Bay Area faces threats from urbanization in addition to climate change. With a rapidly growing population expected to continue to increase over the next century, many lands currently suitable to agriculture and grazing are and will continue to be in high demand for conversion to residential and urban uses. Urbanization projections (acquired from Thorne et al. 2012) suggest that up to 14.7 percent of rangelands can be expected to be converted by 2050 in a business-as-usual scenario, 10.4 percent in a smart-growth scenario (Figure 9).

As acknowledged throughout this discussion, there are many strategies that ranchers could use adapt to climate change, few of them novel, and many of them adding costs to the enterprise of ranching and threatening its economic viability. Ranchers already manage for the next year's forage availability by leaving a certain amount of residual dry matter (RDM); the relationship between germination and RDM is well established and widely monitored (Huntsinger et al. 2007). When forage production in a given year is low, however, a rancher must essentially choose between current and future forage availability. The most common management decisions when rangelands are not producing enough to sustain grazing are to supplement with hay or alfalfa or other forms of feed, and/or to move the herd to greener pastures—toward the north or the coast, up a mountain, or to irrigated areas. Grass-banking, or setting aside rangeland for common use during droughts or other emergencies, has been a successful strategy for the Malpai Borderlands Group in southern Arizona (MBG 2006; Huntsinger et al. 2007), and could offer a solution to reduced reliability of forage production under climate change. Another common practice is to time slaughter or sale of the animals in correspondence with the seasonal production of high-quality forage. A strategy that has not received as much attention until recently is shifting production toward more heat- or drought-tolerant breeds or species of livestock. Each of these has its drawbacks: the extra costs of supplemental feed and moving livestock, the increased competition for irrigation which will continue to increase with greater urban water demand in the future, the limited availability of fresh beef when slaughters are timed to one part of the year, and the added risk or uncertainty of taking on a new and unfamiliar breed. However, with its more temperate climate, the Bay Area, and the North Bay in particular, may be at an advantage over livestock-producing regions in the hotter, drier interior of the state. Meeting the challenges posed by the climate threats the Bay Area faces will be vital to the preservation of rangelands and the ranching industry in the region, which could play an increasingly important role in livestock production in California.

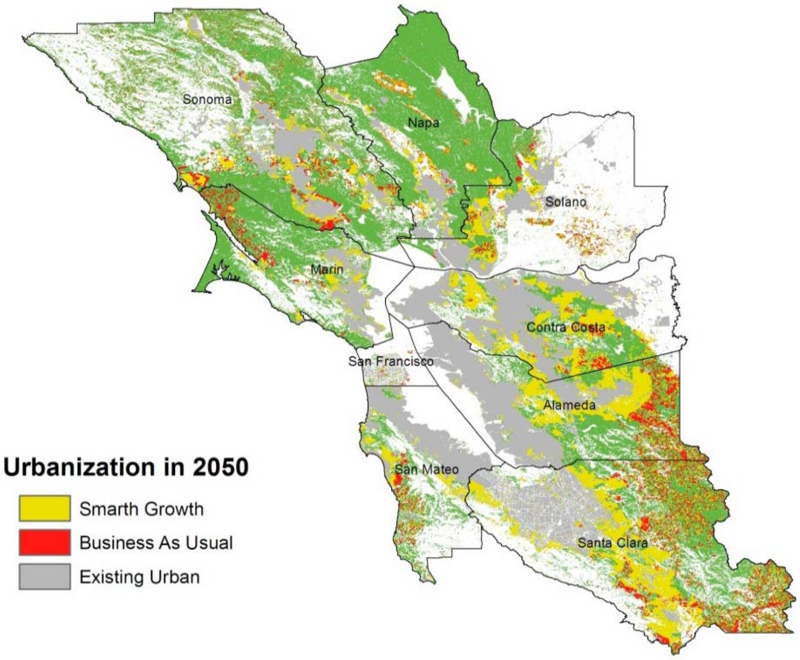


Figure 9. UPLAN Projections for Urban Encroachment into Rangelands by 2050. Green areas show rangeland habitats (not including agricultural land-uses such as pasture); grey areas show existing urban or residential areas. Yellow and red areas show the projected urban areas only where they overlap with current rangelands, for smart growth (yellow) and business-as-usual (red) scenarios. (See Thorne et al. 2012 for more details on UPLAN projections.) Red and yellow areas therefore show the threat to rangelands posed by urbanization.

3.3.2 Wine Grape Production

As with forage production, wine yields may increase with climate change throughout much of the Bay Area (most important, in Napa and Sonoma, where the vast majority of Bay Area wine grapes are grown), but yields are not the only or even most important consideration in wine grape production. Quality will likely decline in the most prized wine regions, with major consequences for the profitability of the industry, unless adaptive measures can be identified and successfully implemented.

The increases in wine yields for Napa and Sonoma Counties are much larger than previous models have forecast at the statewide scale (Lobell et al. 2007). This suggests that yields in Bay Area wine country will be favored by climate change relative to other regions in California. The results presented here were for yield increases or decreases relative to current production, because that held a more meaningful value for a specific region like the Bay Area. However, the analysis was based on an equation calculating wine yield anomalies, or deviations from the state average (Lobell et al. 2006, 2007). Yield anomalies are negative throughout the Bay Area, meaning that Bay Area yields are lower than the state average. These anomalies grow less negative over time in Napa and Sonoma, translating to the overall yield increases shown here (Figure 7). In contrast, yield anomalies are increasingly negative in Solano and Contra Costa Counties, meaning that it will become economically even less attractive to grow grapes in the few places they are currently grown in those counties.

Even with higher yields, profitability in wine country may decline with climate change due to decreasing wine quality. This model suggests that ripening conditions will grow warmer in the future, both because mean temperatures increase in future climates and because the shift in ripening time means that the berries are ripening in August instead of September, which is generally a warmer month. Wine country summer temperatures are currently on the high end of the optimal (15°C–22°C, or 59°F–72°F) range, and its future climate will be pushed out of that envelope (Figure 1).

These results are supported by another way to look at climate impacts on wine quality, the change in area suitable to wine-growing. Diffenbaugh et al. (2011) projected substantial losses of the highest-quality wine-growing areas in Napa County, even though there were equivalent gains in lower-quality areas. Though their analysis takes a different approach to estimating wine quality (total growing degree days for the season, rather than the temperature during ripening month defined by growing degree days, as calculated here), the results are the same: climate conditions in Napa's agricultural acreage moves from being "optimal" wine-production to almost entirely in the "impaired" category, in which high-quality wines are rarely produced (Figure 8). Incorporating information on soil type, as well as climate in a Maximum Entropy approach, Hannah et al. (2012) show that by the end of the century, nowhere in Napa will be suitable for quality wine grape production, and that novel regions for wine production will emerge along the coast.

The results presented here also offer a new insight: Sonoma may fare better, with much of its agricultural area remaining "marginal" by the end of the century in the A2 scenario, which means that high-quality production is still possible, albeit more difficult or less reliable. This emphasizes the importance of regional analyses such as this to highlight such small-scale differences. With the area of optimal wine-producing regions projected to shrink by 50 percent statewide (White et al. 2006) or 37 percent worldwide (Hannah et al. 2012), Sonoma could become an even more important asset in the California's wine-producing portfolio.

As the impacts of climate change and the specific aspects of wine-production that are most sensitive to it are growing increasingly well understood, vineyard adaptation strategies have been discussed widely and are reviewed by Nicholas and Durham (in press). An analysis by Nicholas (2011) rates various measures by six criteria (spatial scale, temporal scale, cost, technical feasibility, cultural acceptability, and effectiveness), using her investigations in wine management in Napa and Sonoma as a case study. While switching growing locations or crops are often suggested as possible adaptation measures that winegrowers could employ in a changing climate, Nicholas identified several constraints to these measures, reducing their overall feasibility. Cultural acceptability presents a major barrier, with growers demonstrating unwillingness to give up land or lifestyle that was part of their family history or identity.

One can envision subtler applications of both of these measures. Production could be moved to different locations on the same vineyard if varying microclimates exist (as is often the case in such topographically diverse region as the Bay Area). Changing varietals or even clones of the same varietal would obviously be much easier and more acceptable to growers than changing crops. However, the time scales over which any adaptation measures related to planting decisions operate present a challenge in wine, which takes decades to reach maturity and therefore faces increased investment and opportunity costs compared to other crops (Bisson et al. 2002). This particular challenge could be (and often is) ameliorated by grafting heat-tolerant varieties onto pre-existing rootstocks, but such options are expensive (estimated at $5,000 per acre) and whether a particular switch in variety could compensate for the changes produced by climate would depend on the specific location and its exposure to climate threats (Nicholas and Durham, in press).

Identifying the specific mechanisms by which wine-growing regions could increase their resilience to the impacts of climate change can help guide management for adaptation. Diffenbaugh et al. (2011) found that increasing the tolerance of growing season days above 20°C (68°F) from 15 to 30 days would eliminate losses in wine quality, at least in the near term (2030–2039). In addition to grafting or replanting more heat-tolerant varieties, simpler and potentially less expensive strategies to enhance heat tolerance in wine in the short term include spraying a kaolin clay to act as a "sunscreen" for the berries, employing overhead sprinklers or evaporative cooling to reduce temperatures in the field, or managing vegetation for shade enhancement (Nicholas and Durham, in press). Both Diffenbaugh et al. (2011) and Nicholas and Durham (in press) agree that shade enhancement in particular is an effective temperature-reduction method without major barriers to implementation, and indeed, is already practiced in some areas. Altering the trellising structure, pruning techniques or timing, and/or row orientation can all help provide more shade, which can reduce the temperature of the berries by more than 10°C (50° F) (Bergqvist et al. 2001).Though such additional management is not without cost, and may have other effects on wine production that need to be weighed against ripening conditions, such substantial reductions in berry temperature could serve the wine industry through climate change well into the next century.

3.3.3 Model Strengths and Weaknesses

Both the forage production and the wine production models benefit from downscaled climate data to explore in fine spatial and temporal (daily) resolution what impacts a future climate will have on agriculture in the San Francisco Bay Area. However, empirical models such as those presented here are only as good as the data from which the relationships were derived.

In the case of wine production, yield data can only be acquired at the county scale, and therefore even though yields are projected at a finer scale, the relationships between yields and climate are based on coarser statewide differences. Including finer-scale variables such as soil type and topography would improve a wine production model if field-level yield data could be acquired. With respect to forecasting changes to wine grape quality, recent work has revealed that modeling ripening time based on growing degree days from April 1 may be an overly simplistic approach (Webb et al. 2011). Nicholas et al. (2011) have found mean August temperatures to be more predictive of wine quality for pinot noir, and while such relationships are obviously very varietal-specific, future work could explore and compare different approaches to modeling quality.

In the case of forage production, data were acquired at a fine-scale field-level resolution, but none of these data were taken within the Bay Area. Hopland Field Station is only ten miles north of Sonoma County, and while the San Joaquin Experimental Range and Sierra Foothill Research and Extension Center are further away (in Madera and Yuba Counties, respectively), they may be representative of the interior parts of the Bay Area like Alameda and Santa Clara counties. However, coastal data would certainly improve the model, and in their absence, model projections for coastal rangelands like those in Marin should be interpreted with caution. Indeed, the shape of the forage growth curves projected for the historical period (shown in Figure 3 in grey) in Marin and Sonoma does not resemble that of the growth curves found in George et al. (2001a). The curves projected for the historical period in Alameda and Santa Clara counties have the shallower slopes during winter months that the George curves display. The coastal regions could have a steeper production curve through the winter than that found at the inland field stations documented by George et al. (2001a), but it is also possible that this model overestimates production in the coastal regions of the Bay Area. Finally, the relationship derived by George et al. (1988), on which the forage production model is based, was dependent on precipitation only in so far as it defined the bounds of the season. Altered precipitation patterns such as longer or more frequent midwinter droughts could change the rules of the game, making the historical relationship between climate and forage production less applicable in future conditions.

Section 4: Conclusions

The aspects of Bay Area agriculture most sensitive to climate change are not yields, but subtler nuances of production. In a future with higher temperatures and altered precipitation patterns, ranchers will need to consider management options for grazing shorter or less-reliable seasons and for forage of questionable nutritional content. Winegrowers will need to find ways to reduce heat stress of their berries or face lower values for their product. These vulnerabilities to climate change are not as easily translated to economic losses as yields are, and how they will weigh against the projected yield gains in forage and wine production is not well understood. However, the main message for the effects of climate change on Bay Area agriculture is that it will present some opportunities as well as some challenges.

In addition to being a major supplier of these valuable agricultural commodities, the Bay Area is an important consumer of agricultural products. Any major metropolitan area demands agricultural production far in excess of what can be produced on its own footprint, but the Bay Area in particular has a growing demand for a locally and sustainably produced food economy. This is where the personal food politics of Bay Area residents may fit in especially well with climate change mitigation and adaptation. Locally sourced food reduces greenhouse emissions, and Bay Area agriculture can support climate change mitigation by producing more of the total food consumed by the people living here. The diversity of Bay Area agriculture could further help provide adaptation options to climate change, as losses in some crops will potentially be offset by gains in others. While it is clearly important to recognize that some crops are more economically valuable than others, and therefore that not all trade-offs will be without economic cost, further diversifying the Bay Area agricultural portfolio could buffer against uncertainty in climate outcomes while better meeting the dietary needs of residents in the Bay Area.

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Glossary

ADD	Accumulated degree-days
BCCA	Bias Corrected Constructed Analogues
°C	centigrade
CIMIS	California Irrigation Management Information System
CNRM	Centre National Recherche Météorologique
CO_2	carbon dioxide
CP	crude protein
DOM	digestible organic matter
°F	Fahrenheit
GDD	growing degree-days
GFDL	Geophysical Fluid Dynamics Laboratory
ha	hectare
IPCC	Intergovernmental Panel on Climate Change
MBG	Malpai Borderlands Group
mm	millimeters
NASS	National Agricultural Statistics Service
NCAR	National Center for Atmospheric Research
P6	precipitation in June
P-9	September of the previous harvest year
PIER	Public Interest Energy Research
ppm	parts per million
RD&D	research, development, and demonstration
RDM	residual dry matter
T	maximum temperature
t	minimum temperature
Tn,4	minimum temperature in April
USGS	U.S. Department of Interior, Geological Survey

Appendix A.

Table A-1. Percent change in peak forage production for 30-year periods (early/historical, mid/historical, and late/historical) in the higher emissions A2 scenario. Max, min and mean values are presented for four climate models, with 95% confidence interval around the means.

	Max	Model	Min	Model	Mean	Error	CI -	CI +
EARLY (2005-2034, compared to 1961-1990)								
Alameda	19.9	NCARCCSM3	4.7	GFDLCM21	13.8	3.5	10.3	17.3
Contra Costa	15.3	CNRMCM3	11.5	GFDLCM21	13.4	0.8	12.6	14.2
Marin	17.2	NCARCCSM3	5.7	CNRMCM3	10.3	2.7	7.6	13.0
Napa	14.6	NCARCCSM3	7.6	GFDLCM21	10.6	1.5	9.0	12.1
Santa Clara	19.1	NCARPCM1	3.2	GFDLCM21	12.5	3.3	9.1	15.8
San Mateo	16.7	NCARCCSM3	7.6	GFDLCM21	12.2	1.9	10.3	14.1
Solano	13.9	CNRMCM3	10.2	GFDLCM21	11.9	0.8	11.1	12.6
Sonoma	12.2	NCARCCSM3	8.4	GFDLCM21	10.6	0.8	9.8	11.4
MID (2035-2064, compared to 1961-1990)								
Alameda	25.5	NCARCCSM3	0.0	CNRMCM3	14.4	6.4	8.0	20.7
Contra Costa	22.6	NCARPCM1	-0.6	CNRMCM4	13.8	5.4	8.4	19.1
Marin	22.3	NCARCCSM3	0.5	CNRMCM5	12.2	5.0	7.2	17.3
Napa	23.4	NCARCCSM4	-0.2	CNRMCM6	13.2	5.5	7.8	18.7
Santa Clara	23.6	NCARCCSM5	0.5	CNRMCM7	14.0	5.7	8.4	19.7
San Mateo	23.8	NCARCCSM6	1.8	CNRMCM8	14.0	5.0	9.0	19.0
Solano	24.2	NCARCCSM7	-0.3	CNRMCM9	13.5	5.5	8.0	19.0
Sonoma	20.1	NCARCCSM8	0.4	CNRMCM10	12.2	4.5	7.7	16.7
LATE (2070-2099, compared to 1961-1990)								
Alameda	33.5	NCARCCSM3	21.5	GFDLCM21	27.3	2.5	24.8	29.8
Contra Costa	27.8	NCARPCM1	23.1	CNRMCM3	25.3	1.2	24.1	26.6
Marin	37.7	NCARCCSM3	18.6	CNRMCM3	29.0	4.0	25.0	32.9
Napa	34.5	NCARCCSM3	27.4	CNRMCM3	31.3	1.5	29.8	32.8
Santa Clara	31.6	NCARPCM1	18.3	GFDLCM21	25.4	2.8	22.6	28.2
San Mateo	36.3	NCARCCSM3	24.1	GFDLCM21	28.6	2.7	25.9	31.3
Solano	30.4	NCARCCSM3	26.2	CNRMCM3	27.5	1.0	26.6	28.5
Sonoma	31.0	GFDLCM21	25.4	CNRMCM3	28.2	1.2	27.0	29.3

Table A-2. Percent change in peak forage production, as in Table A-1, for the lower emissions B1 scenario.

	Max	Model	Min	Model	Mean	Error	CI -	CI +
EARLY (2005-2034, compared to 1961-1990)								
Alameda	25.5	NCARCCSM3	-8.6	GFDLCM21	11.5	7.4	4.1	18.9
Contra Costa	19.3	NCARCCSM3	-7.2	GFDLCM21	9.7	6.0	3.7	15.7
Marin	28.7	NCARCCSM3	-4.8	GFDLCM21	10.8	7.0	3.8	17.9
Napa	23.1	NCARCCSM3	-3.2	GFDLCM21	10.2	5.4	4.8	15.5
Santa Clara	28.0	NCARCCSM3	-7.7	GFDLCM21	12.6	7.6	5.0	20.2
San Mateo	25.3	NCARCCSM3	-3.5	GFDLCM21	11.6	6.0	5.6	17.5
Solano	18.8	NCARCCSM3	-6.7	GFDLCM21	9.2	5.8	3.4	15.0
Sonoma	18.2	NCARCCSM3	-2.7	GFDLCM21	9.3	4.4	4.9	13.7
MID (2035-2064, compared to 1961-1990)								
Alameda	34.3	NCARCCSM3	7.2	GFDLCM21	18.6		12.9	24.3
Contra Costa	28.6	NCARCCSM3	11.5	GFDLCM21	17.9	3.7	14.2	21.6
Marin	34.5	NCARCCSM3	9.2	GFDLCM21	18.1	5.6	12.5	23.8
Napa	33.5	NCARCCSM3	11.5	GFDLCM21	19.3	4.9	14.3	24.2
Santa Clara	36.5	NCARCCSM3	5.5	GFDLCM21	18.0	6.7	11.3	24.7
San Mateo	32.4	NCARCCSM3	8.2	GFDLCM21	17.4	5.2	12.2	22.7
Solano	30.1	NCARCCSM3	10.8	GFDLCM21	17.6	4.3	13.3	21.9
Sonoma	23.7	NCARCCSM3	11.4	GFDLCM21	16.0	2.7	13.3	18.7
LATE (2070-2099, compared to 1961-1990)								
Alameda	48.4	NCARCCSM3	6.0	CNRMCM3	23.5	9.8	13.7	33.3
Contra Costa	39.2	NCARCCSM3	11.0	CNRMCM3	22.7	6.4	16.4	29.1
Marin	41.9	NCARCCSM3	3.8	CNRMCM3	22.1	8.3	13.9	30.4
Napa	39.7	NCARCCSM3	8.0	CNRMCM3	23.2	6.9	16.3	30.1
Santa Clara	46.1	NCARCCSM3	5.7	CNRMCM3	23.1	8.8	14.4	31.9
San Mateo	43.0	NCARCCSM3	7.9	CNRMCM3	23.3	7.8	15.5	31.1
Solano	31.9	NCARCCSM3	10.9	CNRMCM3	20.2	5.0	15.2	25.2
Sonoma	32.9	NCARCCSM3	5.5	CNRMCM3	19.7	6.0	13.8	25.7

Appendix B.

Table B-1. Maximum drought occurrence over a 30-year period in any of the 12x12 km grid cells within each county, for the higher emissions A2 scenario. Drought here is defined in the extreme sense of a season in which germination never occurs (1-week precipitation never exceeds 25 mm). Max, min and mean values are presented for four climate models, with 95% confidence intervals around the mean of the maximum drought occurrence for all four models. For clarity, "max" is the model producing the highest maximum drought occurrence and "min" is the model producing the lowest maximum drought occurrence.

	Max	Model	Min	Model	Mean	Error	CI -	CI +
HISTORICAL (1961-1990)								
Alameda	4	CNRMCM3	0	NCARPCM1	2	0.913	1.087	2.913
Contra Costa	2	CNRMCM3	0	NCARPCM1	1.25	0.479	0.771	1.729
Marin	0		0		0	0.000	0.000	0.000
Napa	0		0		0	0.000	0.000	0.000
Santa Clara	2	CNRMCM3	1	GFDLCM21	1.25	0.250	1.000	1.500
San Mateo	2	CNRMCM3	0	GFDLCM21	0.5	0.500	0.000	1.000
Solano	1	NCARCCSM3	0	CNRMCM3	0.25	0.250	0.000	0.500
Sonoma	0		0		0	0.000	0.000	0.000
EARLY (2005-2034)								
Alameda	2	GFDLCM21	0	CNRMCM3	1	0.408	0.592	1.408
Contra Costa	1	GFDLCM21	0	CNRMCM3	0.5	0.289	0.211	0.789
Marin	0		0		0	0.000	0.000	0.000
Napa	0		0		0	0.000	0.000	0.000
Santa Clara	4	NCARCCSM3	0	CNRMCM3	1.25	0.946	0.304	2.196
San Mateo	0		0		0	0.000	0.000	0.000
Solano	0		0		0	0.000	0.000	0.000
Sonoma	0		0		0	0.000	0.000	0.000
MID (2035-2064)								
Alameda	3	GFDLCM21	0	CNRMCM3	1	0.707	0.293	1.707
Contra Costa	1	NCARCCSM3	0	CNRMCM3	0.25	0.250	0.000	0.500
Marin	0		0		0	0.000	0.000	0.000
Napa	0		0		0	0.000	0.000	0.000
Santa Clara	3	CNRMCM3	0	NCARCCSM3	1	0.707	0.293	1.707
San Mateo	0		0		0	0.000	0.000	0.000
Solano	0		0		0	0.000	0.000	0.000
Sonoma	0		0		0	0.000	0.000	0.000
LATE (2070-2099)								
Alameda	3	CNRMCM3	1	NCARCCSM3	2	0.577	1.423	2.577
Contra Costa	3	CNRMCM3	1	GFDLCM21	1.75	0.479	1.271	2.229
Marin	0		0		0	0.000	0.000	0.000
Napa	1	GFDLCM21	0	CNRMCM3	0.25	0.250	0.000	0.500
Santa Clara	4	CNRMCM3	1	NCARCCSM3	2.25	0.629	1.621	2.879
San Mateo	1	GFDLCM21	0	CNRMCM3	0.25	0.250	0.000	0.500
Solano	2	GFDLCM21	0	NCARPCM1	1	0.408	0.592	1.408
Sonoma	1	GFDLCM21	0	CNRMCM3	0.25	0.250	0.000	0.500

Table B-2. Maximum drought occurrence, as in Table B-1, for the lower emissions B1 scenario.

	Max	Model	Min	Model	Mean	Error	CI -	CI +
HISTORICAL (1961-1990)								
Alameda	4	CNRMCM3	0	NCARPCM1	2	0.913	1.087	2.913
Contra Costa	2	CNRMCM3	0	NCARPCM1	1.25	0.479	0.771	1.729
Marin	0		0		0	0.000	0.000	0.000
Napa	0		0		0	0.000	0.000	0.000
Santa Clara	2	CNRMCM3	1	GFDLCM21	1.25	0.250	1.000	1.500
San Mateo	2	CNRMCM3	0	GFDLCM21	0.5	0.500	0.000	1.000
Solano	1	NCARCCSM3	0	CNRMCM3	0.25	0.250	0.000	0.500
Sonoma	0		0		0	0.000	0.000	0.000
EARLY (2005-2034)								
Alameda	2	GFDLCM21	0	CNRMCM3	1	0.577	0.423	1.577
Contra Costa	1	NCARPCM1	0	CNRMCM3	0.25	0.250	0.000	0.500
Marin	0		0		0	0.000	0.000	0.000
Napa	0		0		0	0.000	0.000	0.000
Santa Clara	2	GFDLCM21	1	CNRMCM3	1.5	0.289	1.211	1.789
San Mateo	0		0		0	0.000	0.000	0.000
Solano	0		0		0	0.000	0.000	0.000
Sonoma	0		0		0	0.000	0.000	0.000
MID (2035-2064)								
Alameda	4	NCARCCSM3	1	CNRMCM3	2.25	0.750	1.500	3.000
Contra Costa	2	NCARCCSM3	0	CNRMCM3	0.5	0.500	0.000	1.000
Marin	0		0		0	0.000	0.000	0.000
Napa	0		0		0	0.000	0.000	0.000
Santa Clara	4	NCARCCSM3	1	GFDLCM21	2.75	0.750	2.000	3.500
San Mateo	1	CNRMCM3	0	GFDLCM21	0.25	0.250	0.000	0.500
Solano	1	CNRMCM3	0	GFDLCM21	0.25	0.250	0.000	0.500
Sonoma	0		0		0	0.000	0.000	0.000
LATE (2070-2099)								
Alameda	4	GFDLCM21	1	CNRMCM3	2	0.707	1.293	2.707
Contra Costa	2	GFDLCM21	1	CNRMCM3	1.25	0.250	1.000	1.500
Marin	0		0		0	0.000	0.000	0.000
Napa	0		0		0	0.000	0.000	0.000
Santa Clara	3	CNRMCM3	1	NCARCCSM3	2.25	0.479	1.771	2.729
San Mateo	0		0		0	0.000	0.000	0.000
Solano	2	NCARCCSM3	0	CNRMCM3	0.75	0.479	0.271	1.229
Sonoma	0		0		0	0.000	0.000	0.000

Appendix C.

Table C-1. Mean length of forage season (days) for 30-year periods in the higher emissions A2 scenario. Season start date is based on germinating rain (first week in which precipitation > 25mm), and season end date is based on a simple water balance model (when cumulative evapotranspiration > cumulative precipitation over a 60 day period). Max, min and mean values are presented for four climate models, with 95% confidence interval around the means.

	Max	Model	Min	Model	Mean	Error	CI -	CI +
HISTORICAL (1961-1990)								
Alameda	156.185	GFDLCM21	138.556	CNRMCM3	146.451	3.826	142.625	150.277
Contra Costa	161.814	GFDLCM21	151.890	CNRMCM3	156.054	2.146	153.907	158.200
Marin	176.607	GFDLCM21	167.730	NCARCCSM3	171.608	2.194	169.414	173.802
Napa	177.329	GFDLCM21	169.110	CNRMCM3	171.243	2.030	169.213	173.273
Santa Clara	166.429	GFDLCM21	145.856	CNRMCM3	154.358	4.379	149.978	158.737
San Mateo	175.679	GFDLCM21	166.517	CNRMCM3	169.396	2.113	167.283	171.509
Solano	161.133	GFDLCM21	152.113	CNRMCM3	156.994	1.894	155.099	158.888
Sonoma	189.828	GFDLCM21	180.710	NCARPCM1	185.351	1.864	183.487	187.216
EARLY (2005-2034)								
Alameda	155.552	NCARPCM1	141.293	CNRMCM3	149.531	3.185	146.346	152.715
Contra Costa	161.919	NCARPCM1	151.857	CNRMCM3	157.763	2.414	155.349	160.176
Marin	172.860	NCARPCM1	162.000	CNRMCM3	169.605	2.560	167.045	172.165
Napa	171.683	GFDLCM21	161.864	CNRMCM3	168.898	2.358	166.539	171.256
Santa Clara	162.265	NCARPCM1	146.950	CNRMCM3	154.567	3.141	151.425	157.708
San Mateo	174.229	NCARPCM1	160.767	CNRMCM3	168.933	2.890	166.044	171.823
Solano	160.154	GFDLCM21	150.333	CNRMCM3	156.472	2.320	154.152	158.792
Sonoma	185.712	GFDLCM21	180.529	CNRMCM3	183.865	1.144	182.721	185.008
MID (2035-2064)								
Alameda	153.626	NCARPCM1	125.022	CNRMCM3	139.348	5.865	133.483	145.213
Contra Costa	162.364	NCARPCM1	129.814	CNRMCM3	148.168	6.786	141.383	154.954
Marin	171.973	NCARPCM1	152.417	CNRMCM3	162.045	3.998	158.047	166.043
Napa	174.014	NCARPCM1	147.529	CNRMCM3	162.133	5.473	156.660	167.606
Santa Clara	157.229	NCARPCM1	125.055	CNRMCM3	145.103	6.954	138.149	152.057
San Mateo	171.692	NCARPCM1	145.900	CNRMCM3	160.686	5.377	155.310	166.063
Solano	161.633	NCARPCM1	129.946	CNRMCM3	148.458	6.661	141.798	155.119
Sonoma	184.332	NCARPCM1	162.650	CNRMCM3	175.448	4.592	170.856	180.041
LATE (2070-2099)								
Alameda	140.248	NCARPCM1	118.004	CNRMCM3	130.059	4.744	125.315	134.804
Contra Costa	150.186	NCARPCM1	127.640	CNRMCM3	138.386	4.700	133.686	143.085
Marin	165.490	NCARPCM1	143.080	CNRMCM3	157.702	5.226	152.476	162.928
Napa	166.212	NCARPCM1	145.450	CNRMCM3	157.389	4.671	152.718	162.060
Santa Clara	147.648	NCARPCM1	119.430	CNRMCM3	132.670	5.785	126.885	138.456
San Mateo	162.350	NCARPCM1	141.496	CNRMCM3	152.230	4.313	147.918	156.543
Solano	152.900	NCARPCM1	133.200	CNRMCM3	141.860	4.114	137.747	145.974
Sonoma	177.037	NCARPCM1	157.878	CNRMCM3	169.116	4.711	164.404	173.827

Table C-2. Length of forage season, as in Table C-2, for the lower emissions B1 scenario

	Max	Model	Min	Model	Mean	Error	CI -	CI +
HISTORICAL (1961-1990)								
Alameda	156.015	GFDLCM21	138.552	CNRMCM3	146.388	3.784	142.603	150.172
Contra Costa	161.517	GFDLCM21	151.821	CNRMCM3	155.911	2.087	153.823	157.998
Marin	176.600	GFDLCM21	167.727	NCARCCSM3	171.576	2.187	169.389	173.763
Napa	176.950	GFDLCM21	169.088	CNRMCM3	171.189	1.922	169.267	173.112
Santa Clara	166.370	GFDLCM21	145.865	CNRMCM3	154.311	4.365	149.946	158.677
San Mateo	175.496	GFDLCM21	166.508	CNRMCM3	169.535	2.026	167.510	171.561
Solano	161.133	GFDLCM21	152.100	CNRMCM3	156.952	1.903	155.049	158.855
Sonoma	189.943	GFDLCM21	180.613	NCARPCM1	185.344	1.907	183.437	187.251
EARLY (2005-2034)								
Alameda	153.204	NCARCCSM3	137.304	GFDLCM21	146.611	3.345	143.266	149.957
Contra Costa	158.288	NCARCCSM3	144.245	GFDLCM21	153.674	3.292	150.383	156.966
Marin	181.623	NCARCCSM3	160.510	GFDLCM21	169.991	5.282	164.709	175.273
Napa	174.571	NCARCCSM3	161.495	CNRMCM3	168.074	3.430	164.644	171.505
Santa Clara	162.536	NCARCCSM3	146.224	GFDLCM21	153.108	3.925	149.183	157.034
San Mateo	176.579	NCARCCSM3	159.233	GFDLCM21	167.976	3.951	164.025	171.927
Solano	157.967	NCARCCSM3	144.275	GFDLCM21	153.242	3.209	150.032	156.451
Sonoma	188.864	NCARPCM1	175.277	GFDLCM21	181.763	3.718	178.045	185.481
MID (2035-2064)								
Alameda	149.644	NCARPCM1	137.759	CNRMCM3	142.854	2.776	140.078	145.630
Contra Costa	161.700	NCARPCM1	146.560	CNRMCM3	153.521	3.312	150.209	156.833
Marin	178.870	NCARCCSM3	162.693	CNRMCM3	170.142	4.115	166.026	174.257
Napa	176.979	NCARCCSM3	159.495	CNRMCM3	169.355	4.349	165.006	173.704
Santa Clara	161.821	NCARCCSM3	141.508	CNRMCM3	150.225	4.563	145.662	154.788
San Mateo	176.025	NCARCCSM3	157.071	CNRMCM3	166.195	4.870	161.324	171.065
Solano	162.042	NCARCCSM3	143.142	CNRMCM3	154.416	4.611	149.805	159.027
Sonoma	185.858	NCARCCSM3	176.343	CNRMCM3	181.190	2.380	178.810	183.570
LATE (2070-2099)								
Alameda	160.478	NCARCCSM3	126.159	CNRMCM3	144.043	7.314	136.728	151.357
Contra Costa	165.443	NCARCCSM3	139.095	CNRMCM3	153.943	5.870	148.074	159.813
Marin	180.417	NCARCCSM3	150.520	CNRMCM3	168.481	6.681	161.800	175.162
Napa	177.443	NCARCCSM3	150.455	CNRMCM3	167.475	6.070	161.405	173.545
Santa Clara	166.398	NCARCCSM3	122.512	CNRMCM3	146.908	9.070	137.838	155.978
San Mateo	181.663	NCARCCSM3	147.121	CNRMCM3	167.029	7.717	159.312	174.746
Solano	163.175	NCARPCM1	140.167	CNRMCM3	152.250	4.920	147.330	157.170
Sonoma	189.739	NCARCCSM3	162.104	CNRMCM3	179.321	6.137	173.184	185.458

Appendix D.

Table D-1. Percent change in wine yields over 30-year periods for the A2 scenario. Max, min and mean values are presented for four climate models, with 95% confidence interval around the means.

	Max	Model	Min	Model	Mean	Error	CI -	CI +
EARLY (2005-2034, compared to 1961-1990)								
Alameda	23.8	GFDLCM21	15.5	NCARPCM1	20.8	1.8	19.0	22.6
Contra Costa	0.3	NCARPCM1	-4.9	GFDLCM21	-3.0	1.2	-4.2	-1.9
Napa	23.6	CNRMCM3	11.4	NCARPCM1	18.0	2.5	15.5	20.5
Santa Clara	8.2	NCARCCSM3	5.5	GFDLCM21	7.1	0.6	6.5	7.8
Solano	2.2	NCARPCM1	-1.2	GFDLCM21	0.6	0.7	-0.1	1.3
Sonoma	34.0	CNRMCM3	14.8	NCARPCM1	23.6	4.1	19.5	27.7
MID (2035-2064, compared to 1961-1990)								
Alameda	37.0	GFDLCM21	29.5	NCARPCM1	33.2	1.6	31.6	34.7
Contra Costa	-2.3	NCARPCM1	-12.3	GFDLCM21	-9.1	2.3	-11.5	-6.8
Napa	37.7	CNRMCM3	25.4	NCARPCM1	32.2	2.6	29.6	34.9
Santa Clara	13.2	NCARCCSM3	7.8	CNRMCM3	10.9	1.2	9.8	12.1
Solano	3.0	NCARPCM1	-4.1	GFDLCM21	-1.1	1.5	-2.6	0.4
Sonoma	57.1	CNRMCM3	34.6	NCARPCM1	48.1	4.9	43.2	53.0
LATE (2070-2099, compared to 1961-1990)								
Alameda	46.2	GFDLCM21	31.4	CNRMCM3	39.2	3.9	35.3	43.2
Contra Costa	-9.3	NCARPCM1	-53.1	CNRMCM3	-35.3	9.3	-44.6	-26.1
Napa	37.1	GFDLCM21	26.5	NCARCCSM3	32.8	2.3	30.5	35.1
Santa Clara	14.4	NCARPCM1	-12.2	CNRMCM3	-0.3	5.5	-5.8	5.2
Solano	-2.5	NCARPCM1	-35.3	CNRMCM3	-22.1	7.0	-29.1	-15.1
Sonoma	63.1	GFDLCM21	46.2	NCARCCSM3	55.1	4.4	50.7	59.4

Table D-2. Percent change in wine yields, as in Table D-1, for the B1 scenario.

	Max	Model	Min	Model	Mean	Error	CI -	CI +
EARLY (2005-2034, compared to 1961-1990)								
Alameda	23.8	NCARCCSM3	11.9	NCARPCM1	20.0	2.7	17.3	22.7
Contra Costa	0.5	NCARPCM1	-9.1	CNRMCM3	-4.5	2.0	-6.5	-2.5
Napa	27.2	CNRMCM3	4.6	NCARPCM1	18.7	5.1	13.5	23.8
Santa Clara	10.9	NCARCCSM3	5.3	NCARPCM1	7.5	1.2	6.3	8.7
Solano	1.3	NCARPCM1	-2.4	CNRMCM3	-0.6	0.8	-1.4	0.1
Sonoma	42.9	NCARCCSM3	8.2	NCARPCM1	29.2	8.4	20.8	37.6
MID (2035-2064, compared to 1961-1990)								
Alameda	40.3	GFDLCM21	26.1	NCARPCM1	33.7	3.0	30.8	36.7
Contra Costa	-0.3	NCARPCM1	-12.3	GFDLCM21	-7.1	2.6	-9.7	-4.5
Napa	41.9	NCARCCSM3	25.4	NCARPCM1	33.1	3.4	29.7	36.5
Santa Clara	14.9	NCARCCSM3	8.9	CNRMCM3	10.8	1.4	9.4	12.2
Solano	3.4	NCARPCM1	-4.9	GFDLCM21	-0.3	1.9	-2.3	1.6
Sonoma	54.7	NCARCCSM3	36.2	NCARPCM1	46.6	4.1	42.5	50.8
LATE (2070-2099, compared to 1961-1990)								
Alameda	45.3	GFDLCM21	40.7	CNRMCM3	42.9	1.1	41.8	44.0
Contra Costa	0.9	NCARCCSM3	-15.9	CNRMCM3	-7.9	4.5	-12.4	-3.4
Napa	42.3	NCARCCSM3	31.6	GFDLCM21	37.3	2.5	34.9	39.8
Santa Clara	21.5	NCARCCSM3	8.3	CNRMCM3	13.8	3.1	10.6	16.9
Solano	8.8	NCARCCSM3	-8.0	GFDLCM21	0.5	4.3	-3.8	4.8
Sonoma	64.0	CNRMCM3	48.6	GFDLCM21	54.4	3.5	50.9	57.9

Appendix E.

Table E-1. Change in date of wine ripening (days earlier) for the A2 scenario. Date of ripening is set by accumulation of 1150 degree days after April 1. Max, min and mean are presented for four climate models, with 95% confidence interval around the means.

	Max	Model	Min	Model	Mean	Error	CI -	CI +
EARLY (2005-2034, compared to 1961-1990)								
Alameda	13.250	GFDLCM21	4.750	NCARPCM1	9.688	1.838	7.849	11.526
Contra Costa	9.400	GFDLCM21	3.200	NCARPCM1	6.850	1.367	5.483	8.217
Napa	11.333	GFDLCM21	4.222	NCARPCM1	8.667	1.605	7.062	10.272
Santa Clara	13.600	GFDLCM21	5.000	NCARPCM1	10.250	1.952	8.298	12.202
Solano	8.727	GFDLCM21	3.273	NCARPCM1	6.614	1.201	5.413	7.815
Sonoma	10.700	GFDLCM21	3.900	NCARPCM1	8.250	1.571	6.679	9.821
MID (2035-2064, compared to 1961-1990)								
Alameda	19.000	CNRMCM3	11.750	NCARPCM1	16.500	1.711	14.789	18.211
Contra Costa	14.600	CNRMCM3	8.600	NCARPCM1	12.400	1.428	10.972	13.828
Napa	17.778	CNRMCM3	10.778	NCARPCM1	15.111	1.627	13.484	16.738
Santa Clara	20.600	CNRMCM3	12.200	NCARPCM1	17.400	1.924	15.476	19.324
Solano	13.909	CNRMCM3	8.364	NCARPCM1	11.955	1.287	10.668	13.242
Sonoma	17.400	CNRMCM3	10.200	NCARPCM1	14.800	1.653	13.147	16.453
LATE (2070-2099, compared to 1961-1990)								
Alameda	36.000	CNRMCM3	19.500	NCARPCM1	28.500	3.410	25.090	31.910
Contra Costa	29.200	CNRMCM3	14.600	NCARPCM1	22.550	3.021	19.529	25.571
Napa	34.111	CNRMCM3	18.222	NCARPCM1	26.944	3.302	23.642	30.247
Santa Clara	37.800	CNRMCM3	20.000	NCARPCM1	29.950	3.716	26.234	33.666
Solano	28.182	CNRMCM3	14.364	NCARPCM1	22.136	2.873	19.263	25.009
Sonoma	35.000	CNRMCM3	18.100	NCARPCM1	27.450	3.502	23.948	30.952

Table E-2. Change in date of wine ripening, as in Table E-1, for the B1 scenario

	Max	Model	Min	Model	Mean	Error	CI -	CI +
EARLY (2005-2034, compared to 1961-1990)								
Alameda	14.500	CNRMCM3	4.500	NCARPCM1	10.438	2.214	8.224	12.651
Contra Costa	11.000	CNRMCM3	3.400	NCARPCM1	7.650	1.636	6.014	9.286
Napa	13.333	CNRMCM3	3.889	NCARPCM1	9.306	2.043	7.263	11.348
Santa Clara	15.400	CNRMCM3	4.800	NCARPCM1	10.950	2.291	8.659	13.241
Solano	10.273	CNRMCM3	3.091	NCARPCM1	7.273	1.538	5.735	8.811
Sonoma	12.900	CNRMCM3	3.700	NCARPCM1	8.800	1.952	6.848	10.752
MID (2035-2064, compared to 1961-1990)								
Alameda	18.000	CNRMCM3	7.250	NCARPCM1	13.875	2.337	11.538	16.212
Contra Costa	13.400	CNRMCM3	5.000	NCARPCM1	10.200	1.838	8.362	12.038
Napa	16.667	CNRMCM3	6.778	NCARPCM1	12.667	2.118	10.548	14.785
Santa Clara	19.200	CNRMCM3	7.800	NCARPCM1	14.850	2.502	12.348	17.352
Solano	12.818	CNRMCM3	5.000	NCARPCM1	9.932	1.707	8.225	11.638
Sonoma	16.600	CNRMCM3	6.300	NCARPCM1	12.425	2.195	10.230	14.620
LATE (2070-2099, compared to 1961-1990)								
Alameda	23.250	CNRMCM3	11.750	NCARPCM1	17.625	2.561	15.064	20.186
Contra Costa	18.200	CNRMCM3	9.000	NCARPCM1	13.400	2.051	11.349	15.451
Napa	21.444	CNRMCM3	11.333	NCARPCM1	16.278	2.246	14.031	18.524
Santa Clara	24.600	CNRMCM3	12.800	NCARPCM1	18.600	2.586	16.014	21.186
Solano	17.273	CNRMCM3	8.727	NCARPCM1	12.977	1.861	11.116	14.839
Sonoma	21.100	CNRMCM3	11.000	NCARPCM1	15.950	2.258	13.692	18.208

Appendix F.

Table F-1. Average temperature during the month of wine ripening, which dictates wine grape quality, for the A2 scenario. Conditions for producing high quality wines are considered optimal when in the range of 15°C–22°C, marginal in the range of 22°C–24°C, and impaired above 24°C. Max, min and mean values are presented for four climate models, with 95% confidence interval around the means.

	Max	Model	Min	Model	Mean	Error	CI -	CI +
HISTORICAL (1961-1990)								
Alameda	20.105	NCARPCM1	19.826	GFDLCM21	19.963	0.076	19.887	20.040
Contra Costa	23.282	NCARPCM1	22.915	CNRMCM3	23.073	0.076	22.997	23.149
Napa	20.200	NCARPCM1	19.837	GFDLCM21	20.000	0.082	19.918	20.082
Santa Clara	20.188	NCARPCM1	19.899	GFDLCM21	20.039	0.063	19.976	20.102
Solano	22.899	NCARPCM1	22.599	CNRMCM3	22.703	0.067	22.636	22.770
Sonoma	19.194	NCARCCSM3	18.890	GFDLCM21	19.058	0.075	18.983	19.133
EARLY (2005-2034)								
Alameda	22.481	CNRMCM3	20.980	NCARPCM1	21.777	0.315	21.461	22.092
Contra Costa	25.540	CNRMCM3	24.100	NCARPCM1	24.777	0.296	24.480	25.073
Napa	22.369	CNRMCM3	21.057	NCARPCM1	21.739	0.275	21.464	22.014
Santa Clara	22.364	CNRMCM3	20.956	NCARPCM1	21.691	0.298	21.393	21.989
Solano	25.150	CNRMCM3	23.720	NCARPCM1	24.378	0.294	24.083	24.672
Sonoma	21.069	CNRMCM3	19.944	NCARPCM1	20.517	0.249	20.269	20.766
MID (2035-2064)								
Alameda	24.027	CNRMCM3	21.898	NCARPCM1	22.967	0.449	22.519	23.416
Contra Costa	26.948	CNRMCM3	24.998	NCARPCM1	25.917	0.400	25.517	26.317
Napa	23.870	CNRMCM3	21.880	NCARPCM1	22.856	0.413	22.442	23.269
Santa Clara	23.745	CNRMCM3	21.850	NCARPCM1	22.774	0.402	22.372	23.176
Solano	26.561	CNRMCM3	24.543	NCARPCM1	25.488	0.415	25.073	25.903
Sonoma	22.493	CNRMCM3	20.751	NCARPCM1	21.564	0.381	21.184	21.945
LATE (2070-2099)								
Alameda	27.801	CNRMCM3	23.419	NCARPCM1	25.266	0.916	24.350	26.182
Contra Costa	29.686	CNRMCM3	26.871	NCARPCM1	28.039	0.592	27.447	28.630
Napa	27.683	CNRMCM3	23.384	NCARPCM1	25.135	0.907	24.227	26.042
Santa Clara	27.364	CNRMCM3	23.225	NCARPCM1	24.888	0.877	24.012	25.765
Solano	29.291	CNRMCM3	26.289	NCARPCM1	27.586	0.624	26.962	28.209
Sonoma	26.625	CNRMCM3	22.105	NCARPCM1	23.809	0.977	22.832	24.786

Table F-2. Average temperature during wine ripening, as an indicator of wine quality as defined in Table F-1, for the lower emissions B1 scenario

	Max	Model	Min	Model	Mean	Error	CI -	CI +
HISTORICAL (1961-1990)								
Alameda	20.105	NCARPCM1	19.826	GFDLCM21	19.963	0.076	19.887	20.040
Contra Costa	23.282	NCARPCM1	22.915	CNRMCM3	23.073	0.076	22.997	23.149
Napa	20.200	NCARPCM1	19.837	GFDLCM21	20.000	0.082	19.918	20.082
Santa Clara	20.188	NCARPCM1	19.899	GFDLCM21	20.039	0.063	19.976	20.102
Solano	22.899	NCARPCM1	22.599	CNRMCM3	22.703	0.067	22.636	22.770
Sonoma	19.194	NCARCCSM3	18.890	GFDLCM21	19.058	0.075	18.983	19.133
EARLY (2005-2034)								
Alameda	22.914	CNRMCM3	20.826	NCARPCM1	21.773	0.455	21.318	22.228
Contra Costa	25.746	CNRMCM3	23.841	NCARPCM1	24.698	0.398	24.300	25.096
Napa	22.788	CNRMCM3	20.781	NCARPCM1	21.706	0.435	21.271	22.141
Santa Clara	22.640	CNRMCM3	20.822	NCARPCM1	21.670	0.397	21.274	22.067
Solano	25.389	CNRMCM3	23.400	NCARPCM1	24.297	0.416	23.880	24.713
Sonoma	21.447	CNRMCM3	19.811	NCARPCM1	20.525	0.377	20.148	20.902
MID (2035-2064)								
Alameda	24.076	CNRMCM3	21.411	NCARPCM1	22.769	0.549	22.220	23.319
Contra Costa	26.944	CNRMCM3	24.466	NCARPCM1	25.622	0.510	25.112	26.132
Napa	23.857	CNRMCM3	21.407	NCARPCM1	22.631	0.504	22.127	23.134
Santa Clara	23.683	CNRMCM3	21.384	NCARPCM1	22.544	0.474	22.070	23.018
Solano	26.533	CNRMCM3	24.005	NCARPCM1	25.204	0.519	24.685	25.723
Sonoma	22.451	CNRMCM3	20.288	NCARPCM1	21.345	0.443	20.901	21.788
LATE (2070-2099)								
Alameda	24.850	CNRMCM3	22.269	NCARPCM1	23.472	0.530	22.942	24.003
Contra Costa	27.656	CNRMCM3	25.121	NCARPCM1	26.198	0.530	25.668	26.728
Napa	24.580	CNRMCM3	22.232	NCARPCM1	23.332	0.484	22.848	23.817
Santa Clara	24.406	CNRMCM3	22.062	NCARPCM1	23.129	0.483	22.647	23.612
Solano	27.193	CNRMCM3	24.708	NCARPCM1	25.804	0.515	25.289	26.319
Sonoma	23.208	CNRMCM3	21.010	NCARPCM1	21.971	0.457	21.514	22.429