# Modeling climate change impacts on wine grape yields and quality in California

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**Abstract**

Improved assessment of wine grape yield and quality responses to future climate are needed to understand potential impacts of climate change on the wine industry and to prioritize adaptation strategies. Here, we used simple climate and quality metrics suggested by the literature to project rough quality categories for California under future climate change, using two climate models and two emissions scenarios to capture a range in both scientific and socioeconomic uncertainty. We then developed quantitative models of relationships between historical climate patterns and wine grape yields in California, and applied these using a larger suite of climate models and emissions scenarios to project future wine grape yields in California.

Our initial evaluation of potential changes in wine grape quality was based on the temperature experienced during ripening. We found that the temperature increases projected for California's winegrowing regions over the coming century could shift large areas of the state from currently optimal conditions to climate conditions which make high-quality wine production more difficult, especially under higher warming resulting from either a more sensitive climate or higher greenhouse gas emissions.

We further evaluated the effect of climate change on wine grape yields in California using outputs from: multiple climate models, to represent scientific uncertainty in the sensitivity of the climate system to human emissions; multiple emissions scenarios, to evaluate uncertainty in future emissions from human activities; and finally, multiple statistical yield models, to evaluate yield response uncertainties. The best-fit yield model found higher yields associated with moderate nighttime temperature in April and higher precipitation in June and the October preceding harvest ($R^2_{adj}$ = 0.63). Applying this model to future climate change projections, we found that wine grape yields in California as a whole are likely to experience a decline of 5% by the end of the century if we impose that future yield changes from climate cannot exceed historical extremes, with 90% confidence intervals including both climate and crop uncertainties of +8 to -13%. If we allow future yield changes to exceed historical extremes, yields are likely to decline by 10% (90% confidence intervals: +10 to -39%). Under the current climate scenarios, regions projected by our models to have high yields overlap with the currently planted areas, but shift towards the coast and the north with future warming. While wine grape yield is highly manipulated by viticulturists, a warming climate may limit management options by stressing the growing and ripening capacities of vines.

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California dominates the U.S. wine market, producing over 90% of the country's wine grapes, the most valuable U.S. fruit crop (Goodhue *et al.*, 2002). California is also the fourth-largest producer of wine in the world, with approximately 6% of global wine market share, after the nations of France (22%), Italy (21%), and Spain (12%) (Heien and Martin, 2003). California wine exports in 2003 were valued at $672 million (MFK Research, 2006).

The wine industry in California has two major modes of production: generally large-scale, high-volume production in fertile, warm to hot areas in the Great Central Valley (which in 2002 accounted for 55% of vineyard area, 72% of winegrape production, and 29% of winegrape value), and the generally higher-priced, smaller-scale production in usually cooler areas along the coast (which in 2002 represented 45% of vineyard area, 28% of wine grape production, and 71% of winegrape value in the state) (Heien and Martin, 2003).

Producing high-quality wine requires both human skill in vineyard management and winemaking, and environmental conditions suited to the optimal ripening of the grape on the vine. As wine grapes are long-lived perennial crops often in production for many decades, they are potentially sensitive to changes in climate.

## I. Methods

A brief outline of our methods and key findings is summarized here; interested readers are referred to our published work (Hayhoe *et al.*, 2004; Lobell *et al.*, 2006, 2007) for full details.

### *I.1. Climate modeling*

We used multiple climate models to capture some of the uncertainties associated with the physical climate system and its sensitivity to greenhouse gas forcing, and multiple emissions scenarios to bracket much of the range of uncertainty associated with future pathways for greenhouse gas emissions.

For estimates of future wine grape quality, we used the lower-sensitivity PCM climate model and the medium-sensitivity HadCM3 climate model for the A1fi and B1 emissions scenarios (atmospheric $CO_2$ concentrations by 2100 of ~970 parts per million (ppm) and ~550ppm, respectively) (Hayhoe *et al.*, 2004).

For yield estimates, we used six GCMs with daily projections available for both day and nighttime temperatures: CSIRO, GISS, INM, MIROC high and medium resolution, and NCAR CCSM3 (Lobell *et al.*, 2006) for three emissions scenarios: A2 (medium high), A1B (medium), and B1 (lower) (with 2100 $CO_2$ concentrations of about 850, 720, and 550ppm, respectively) (Nakicenovic *et al.*, 2000).

### *I.2. Quality*

Projected future temperatures from the multiple climate models and emissions scenarios were used to estimate: 1) wine grape ripening time based on accumulated growing degree days (GDD), and 2) average monthly temperature at the GDD-derived ripening month, a factor influencing potential quality (Gladstones, 1992). We estimated that grape ripening requires between 1150-1300 GDD above the threshold of 10ºC from April to October inclusive (Amerine and Winkler, 1944). These ripening estimates include the range of the top 5 wine grape varieties in California (Chardonnay, Cabernet Sauvignon, Zinfandel, Colombard, and Merlot), which account for more than 50% of the annual crush (Gladstones, 1992; CASS, 2005). For the top ten grape-growing counties in California, we compared modeled temperature averages for mid-century (2020-2049) and end-of-century (2070-2099) to a baseline of GDD accumulation and observed average temperatures during the ripening month from weather stations.

We used the monthly average temperature at the time of ripening as an estimate of potential impact of temperature on grape quality. Ripening month average temperature ranges were designated as optimal (15-22°C), marginal (22-24°C), or impaired (above 24°C) for producing high-quality wine grapes. This definition of high-quality ripening conditions establishes a baseline ability to produce grapes consistent with the expression of desired variety characteristics, not a guarantee of achieving quality. Optimal classification means there are many places where high-quality vineyards can thrive, where moderate temperatures allow the accumulation of sugars to be balanced by appropriate declines in acid levels and the development and retention of desired flavor and aroma compounds. In marginal conditions, acceptable sites will be more rare, and likely in different locations than the best sites for present conditions. When conditions are impaired, it is likely that only a few sites will be appropriate for high-quality vineyards, and those will almost certainly be different locations than those that are best under current conditions. Impaired conditions nearly always reduce quality for most table wines (Gladstones, 1992).

### *I.3. Historical Yields*

To examine the effect of historical climate on the yields of wine grapes (and 11 other crops; see Lobell *et al.*, 2007), we obtained state yield data for all cultivars of wine grapes aggregated together from 1980 to 2003 from California county agricultural commissioners (CASS, 2004). To avoid the confounding effect of changes in yield due to management and cultivar changes, we removed a linear trend from wine grape yields to produce a time series of yield anomalies to correlate with historical weather. For wine grapes, the trend over 24 years was a modest increase of 9.4% (Lobell *et al.*, 2007).

To develop the historical climate dataset, we obtained daily weather records for the same period for 382 cooperative weather stations throughout California from the California Climate Change Center at the Scripps Institute of Oceanography (M. Tyree, personal communication). We then generated a monthly time series for the average daily minimum and maximum temperatures (thus allowing us to distinguish effects of day and nighttime temperatures on crop yields) and precipitation. We developed a statewide climate time series for wine grapes by weighting each county by the relative area of wine grapes in that county in 2003 (Lobell *et al.*, 2007).

The next step was to use linear regression models to identify key climate variables and periods that explained anomalies in wine grape yields. We tested the influence of the three climate variables in months from January the year before harvest to December the year of harvest, and included a second-order polynomial regression to capture potential non-linear effects of climate on yields (Lobell *et al.*, 2007). The predictive power of each regression was assessed using its coefficient of determination ($R^2$).

The three most powerful climate variables during key months were then included in a multiple regression using the climate variables as predictors. These models were developed using both objective (good model accuracy) and subjective (physiologically reasonable) criteria. Finally, to assess the contribution of climate to yield trends, the original yield data (without the linear trend removed) was modeled as a function of time and the selected climate variables (Lobell *et al.*, 2007).

We took several steps to avoid developing models with a high $R^2$ that did not, in fact, represent an important control of climate on yields. First, we examined correlation coefficients of the monthly climate variables to avoid selecting models based on false correlations. Second, we developed statistical criteria for model significance based on evaluating our crop models for a normally distributed time series of random variables to ensure the climate variables we selected were unlikely to have a high $R^2$ purely by chance (see Lobell *et al.*, 2007).

### *I.4. Future yields*

We used the historical climate and yield models we developed for six crops, including wine grapes, to project yields under future climates, using the climate models and scenarios discussed above. We performed analyses to account for two types of uncertainty in the crop models we developed. First, we used 100 replicates of bootstrap resampling of the historical record to generate new estimates of the model coefficients (Efron and Gong, 1983), then applied these models repeatedly to the simulated climate, to account for the fact that the models we developed were based on discrete historical observations and do not perfectly capture historical climate-yield relationships (Lobell *et al.*, 2006). Second, we applied the crop models with and without allowing yields to exceed historical extremes, to account for the fact that future climate may exceed the historical ranges upon which the models were developed (Lobell *et al.*, 2006).

## II. Results

### *II.1. Wine grape quality under future climate change*

Across all models and scenarios, our GDD calculations estimated earlier ripening (by up to 1-2 months) at higher temperatures. This produced shifts from optimal to marginal or impaired conditions across major grape-growing regions in the state by the end of the century, with the notable exception of the cool coastal counties of Monterey and Mendocino. Some differences are apparent between higher and lower emissions scenarios and between climate models (Figure 1).

All scenarios show a shift from current marginal to impaired conditions for the Central Valley grape-growing regions by mid-century and beyond, with no significant difference between the higher and lower emissions scenarios.

By mid-century, all simulations show a slight shift to the warmer end of the optimal range in currently optimal grape-growing zones in the North Coast Wine Country (Sonoma and Napa Counties) and Cool Coastal areas (Monterey and Mendocino Counties). The average warming over the state for summer temperatures is between 1.2-3.1ºC relative to the baseline (Hayhoe *et al.*, 2004), depending on climate model and emissions scenario (Figure 1).

For the end of century time period, average statewide summer temperature increase is 2.15-4.6°C under the lower B1 emissions scenario, and between 4.1-8.3°C under the higher A1fi scenario (Hayhoe *et al.*, 2004). This is expected to push the timing of grape harvest an average of 1–2 months earlier relative to the reference period, with harvest occurring at higher temperatures. This produces a shift from optimal to marginal and marginal to quality-impaired regions. Under the lower B1 emissions scenario, the Cool Coastal region remains in the optimal range, with all other regions becoming either marginal or impaired. Under the higher A1fi emissions scenario, all locations are impaired under the HadCM3 climate model. The PCM model predicts the Central Coast (San Luis Obispo and Monterey Counties) to be marginal and the Cool Coastal to be on the high end of the optimal range (Figure 1).

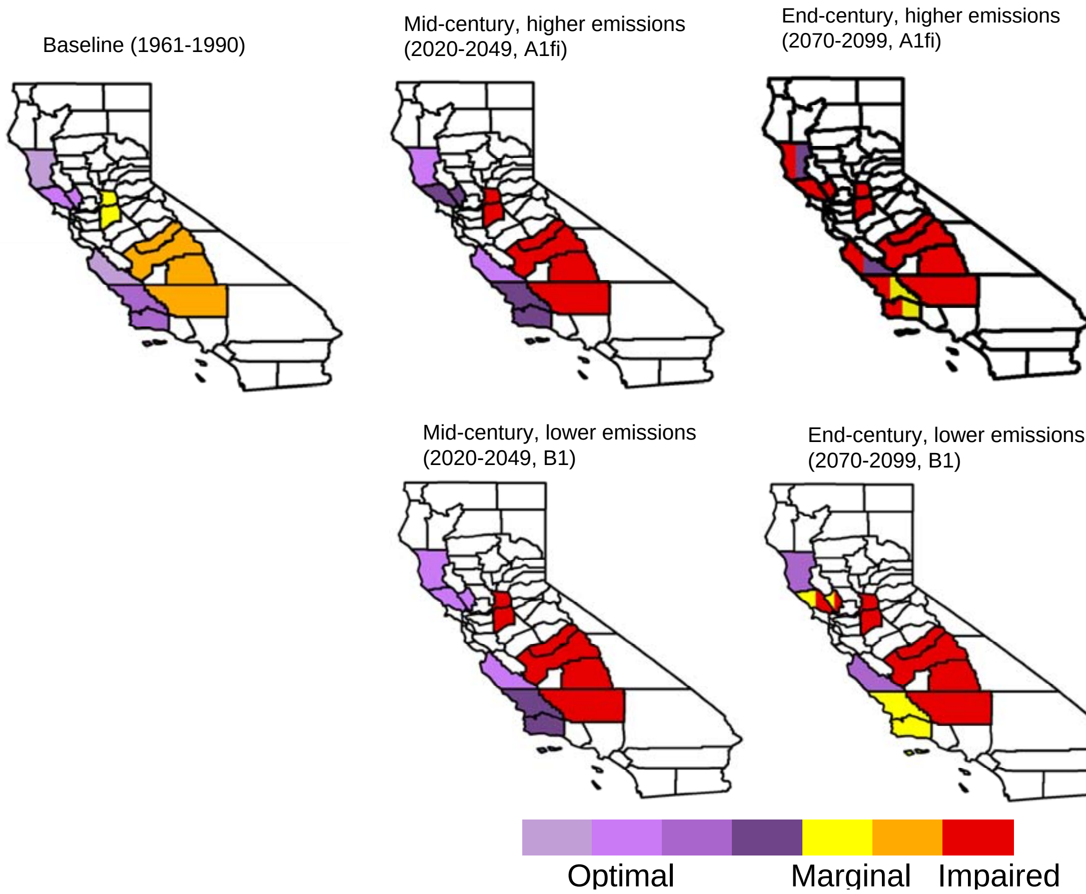


*Figure 1. Baseline and projected future wine grape quality in California. See text for explanation of classification categories. Agreement between the two climate models was strong for mid-century. Where results were different for different climate models at the end-of-century, the HadCM3 results are shown on the left, and PCM on the right within a county.*

### *II.2. Modeling Historical Wine Grape Yields*

The selected model for wine grape yields was:

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

where Y represents yield anomaly (in units of tons acre$^{-1}$), $T_n$ is monthly average minimum temperature (°C), P is precipitation (mm), and the subscript number represents the month of the climate variable used, with negative values indicating a year prior to harvest (Lobell *et al.*, 2006). This models shows that wine grape yields were favored by a warm April and higher precipitation in June and in the September before harvest ($R^2$adj=0.63) (Figure 2). Large yield increases were seen with warming above the coldest April temperatures; however, California is currently within 1°C of the optimum April nighttime temperature for promoting wine grape yields, above which yields are projected to level off and then decline (Lobell *et al.*, 2006).

Model results for table grapes may also be of interest. Table grape yields were favored by higher precipitation in the October prior to harvest, moderate July nighttime temperatures (between an average of 16-18°C), and warm April temperatures ($R^2$adj=0.71; see Lobell *et al.* 2006 for equation). Statewide, California is just past this average now, and our models suggest that increased July nighttime temperatures would tend to decrease table grape yields (Lobell *et al.*, 2007).

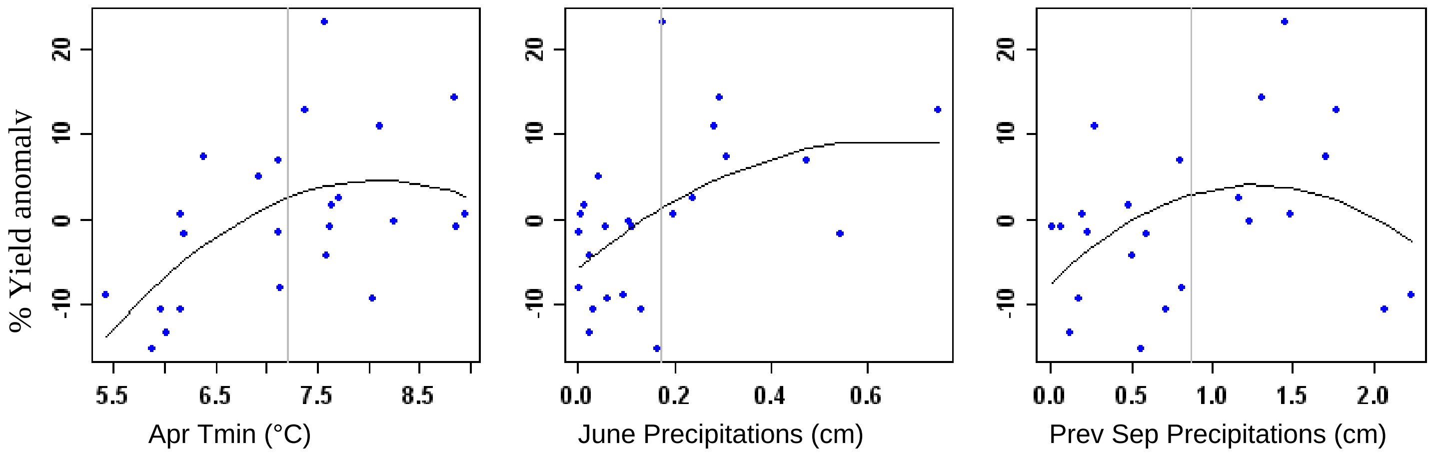


*Figure 2. Observed (points) and modeled (curve) yield anomaly vs. most important climate anomalies for California statewide wine grape yields, 1980-2003. Vertical line shows 1980-2003 statewide average temperature or precipitation.*

Potential mechanisms for these critical periods, based on wine grape physiology, are speculative and could be further tested in field or greenhouse experiments. April day and nighttime temperatures were highly correlated, and both promoted higher yields; warm April nights avoid frost damage during a sensitive growing period, while warm April days provide a good start to the growing season. The importance of precipitation in June fits with the findings of Matthews *et al.* (1987) that yields are more sensitive to water limitation before *veraison*, which typically occurs in July in California. Growers in California often withhold irrigation before *veraison* in an effort to increase perceived quality. Finally, because California tends to be warm enough for vine photosynthesis well into the fall, and irrigation usually ceases upon harvest around September, rain in the autumn in the year before harvest may benefit the vine by removing either water or nutrient limitations to continued vine metabolism. This might allow further cluster primordia development and further vegetative growth and cane hardening, resulting in better cold-weather survival and increased yields the following year. At least a few California viticulturists seem to recognize this relationship by conducting an extended irrigation event following harvest in the autumn (Eve-Lyn Hinckley, Stanford University, personal communication).

### *II.3. Modeling Future Wine Grape Yields in a Changing Climate*

Simulations by multiple climate models for a range of future emissions scenarios showed that temperature changes for California are likely to show an annual average increase of 1-3°C by 2050 and 2-6°C by 2100, depending on the sensitivity of the climate system and on human emissions over the coming century, both of which contributed significantly to the projected temperature range. Across all climate models, the average end-century temperature increases under the medium A1B versus the lower B1 scenario was approximately +1°C, and the average increase between the A1B and medium-high A2 scenarios was an average of a further +0.5°C. Within one emissions scenario across all climate models, the range for the temperature projection was approximately ±1°C from the average increase for both the B1 and A2 scenarios, and approximately ±1.5°C for the A1B scenario (see Figure 2 of Lobell *et al.*, 2006). Projected changes in precipitation varied between climate models from +40% to -40%, showing no definitive direction of change. The next few decades (until 2020) are likely to be within the range of historical variability in temperature; after that, temperatures begin to extend beyond the historical range (Lobell *et al.*, 2006).

We found that the median wine grape yields across the state of California by the end of the century were projected to decline by 10%, with 90% confidence intervals from +10 to -39% (Figure 3). Under the very conservative assumption that yield anomalies would not exceed the historical range, even if climate did exceed the historical range, the median wine grape yields by the end of the century were projected to decline by 5%, with 90% CI of +8 to -13% (Figure 3) (Lobell *et al.*, 2006).

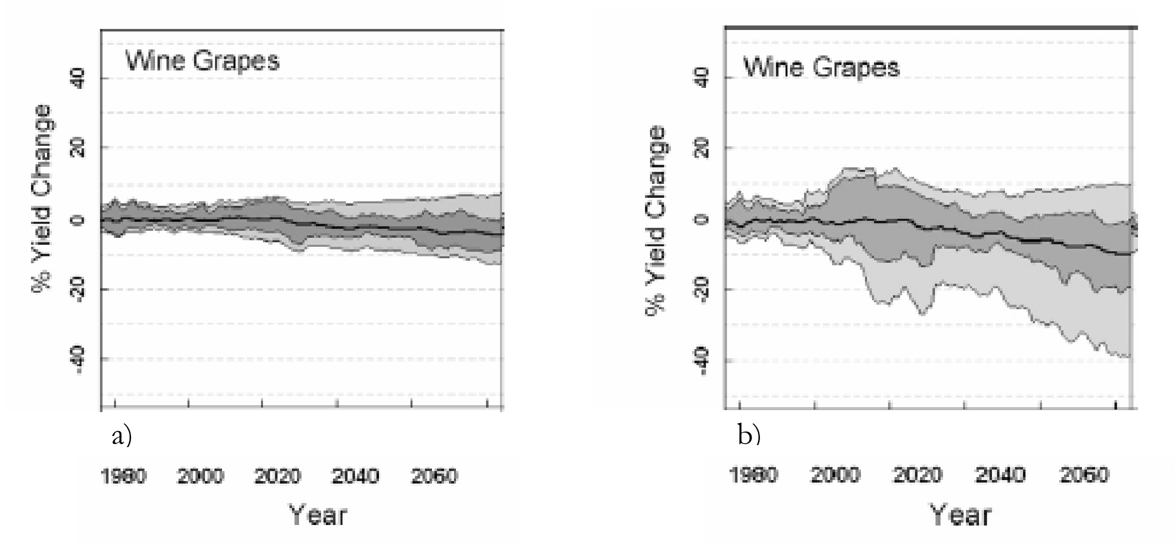


*Figure 3. Wine grape yield changes associated with future climate projections. Yields are expressed as units of % anomaly from 2000-2003 average yields, and plotted as 19-year running averages to highlight trends. Black line shows median projection. Dark shaded area shows 90% confidence interval after accounting for climate uncertainty (multiple climate models and emissions scenarios) and light shaded area shows 90% confidence interval after accounting for both climate and crop yield uncertainty (using bootstrap resampling for crop models). In Figure (a), yield anomalies were constrained to historical extremes, while in Figure (b), yield anomalies were allowed to exceed historical extremes (see text).*

We conducted an analysis to determine which counties were currently suitable to produce favorable wine grape yields, and how those might shift under future climate change (Lobell *et al.*, 2006). Currently, 25 of California's 58 counties have climate conditions suitable to produce at least 95% of the current average yield. Wine grape plantings are concentrated in these counties, demonstrating that viticulturists have selected planting areas well (Figure 4). With a 2°C average temperature increase, suitable counties will shift westward along the entire coastline and the number of suitable counties will actually expand to 38, which overlaps with 77% of currently planted area (Figure 4). With a 4°C average temperature increase, suitable areas shift to northern half of the state, focused in coastal and Sierra foothill regions. Under this scenario, 26 counties are suitable to favorable wine grape yields, but only 33% of currently planted wine grape vineyards are in those counties. Warming of this magnitude would create substantial changes from current planting styles and areas (Figure 4).

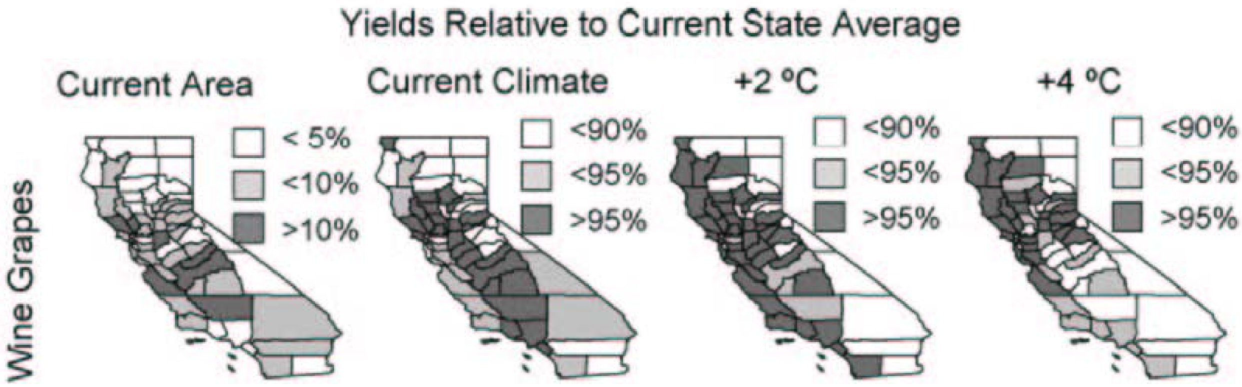


*Figure 4. Map of current statewide area of wine grapes, current yield of wine grapes, and projected future yields relative to current state average.*

## III. Conclusions

Climatic conditions for high-quality grape-growing regions in California are roughly similar under higher and lower emissions scenarios by mid-century, although the higher scenario is projected to result in conditions likely to favor different grape varieties than those favored by historical conditions. More differences between emissions scenarios emerge towards the end of the century, when retaining areas of optimal high-quality grape-growing conditions are more likely under the lower emissions scenario.

We developed models that were successful in using simple climate variables to explain a substantial amount of historical wine grape yield variability. When we applied these models to future climate projections, we found a small likelihood of climate change benefiting wine grape yields in California. Although they are less impacted than other perennial crops, wine grape yields are still likely to be negatively impacted by climate warming (Lobell *et al.*, 2006). A larger and more negative impact on yields and on the areas conducive to good wine grape yields is projected under greater warming.

Significant adjustments may be required to adapt wine grape varieties, management, and growing regions to a changing climate over the coming century, and the magnitude of these adjustments could be affected by human emissions of greenhouse gases during that time. Greater warming will likely place greater stresses on high-quality winegrowing, particularly by the end of the 21st century.

This work is useful in establishing a baseline for our understanding of the effects of climate and climate change on winegrowing in California. Still, more work is needed to examine in more detail the effects of climate on wine grape yields and quantifiable metrics of quality for particular varieties and regions, since there is likely to be considerable variability between regions and varieties not evident at the state scale. Future work should also explicitly include the role of vineyard management in affecting wine grape quality and yields, as this will make this line of research of greater interest and use to viticulturists.

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