

## Abstract

Grapes are the most valuable fruit crop in the nation, with wine grapes making up three-quarters of total grape value. California grows over 90% of wine grapes in the U.S., with an annual crop value of \$3.2 billion. 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.

We used two state-of-the-art climate models (PCM and HadCM3), driven by scenarios of higher and lower greenhouse gas emissions (IPCC SRES scenarios A1fi and B1), to project climate in California over the coming century. Projected temperatures were used to estimate 1) wine grape ripening time based on accumulated growing degree days, and 2) average monthly temperature at ripening, a factor influencing potential quality. Ripening temperature ranges were designated as optimal, marginal, or impaired for producing high-quality wine grapes. 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 growing degree day accumulation and observed average temperatures from weather stations.

Across all models and scenarios, earlier ripening at higher temperatures produced shifts from optimal to marginal or impaired conditions across major grape-growing regions in the state by the end-of-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. 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 the emissions pathway followed during that time.

## Background & Motivation Climate and Grapes

- Grapes for wine production are widely grown throughout the world, but a combination of environmental factors (temperature, sunshine, slope, aspect, soil, etc.) and careful management (including matching variety to site, viticultural practices, and winemaking skill) is needed to produce the highest quality wines.



- Generally, the best wines are produced from grapes that barely achieve maturity at a given site, because long, slow, even ripening of the berries imparts the maximum flavor, balance, and concentration in the resulting wine (Berry, 1990).

- Previous studies have examined potential impacts of climate change on California wine grapes (e.g., Nemani et al., 2001), but this was the first study to compare results from two climate models, two emission scenarios, and to examine impacts at the end of the current century.

## Economic Importance of Grapes in California

- Grapes are the second most valuable crop in California at \$3.2 billion (CASS, 2003).
- A recent report by MKF Consultants (2004) estimated state winery revenues of \$8.7 billion, and an "overall economic impact" of the wine industry of \$45 billion (including jobs, taxes, tourism, etc.).

## Study Questions

- Are projected future climate changes likely to impact continued production of high-quality wine grapes in California?
- Is there is a significant difference in the impact from different emission scenarios on future climate and potential grape quality in California?

## Methods

### Climate Models and Scenarios

- We used two global climate models with different sensitivities** (i.e., temperature increase in response to increasing greenhouse gases) to capture some of the uncertainties associated with the physical climate system and its responses to greenhouse gas forcing.
  - The Parallel Climate Model (PCM) developed by the National Center for Atmospheric Research/Department of Energy, which has low sensitivity.
  - The U.K. Meteorological Office Hadley Centre Climate Model, version 3 (HadCM3), which has medium sensitivity.

- We also used two emissions scenarios** from the Special Report on Emission Scenarios (SRES) developed by the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic et al., 2000). These scenarios were selected to bracket much of the range of uncertainty associated with future pathways for greenhouse gas emissions.
  - The A1fi (fossil intensive) scenario ["higher emissions"] envisions economic growth and globalization resulting in increased energy use and industrial production, with a focus on fossil energy sources, resulting in an atmospheric CO<sub>2</sub> concentration of ~970ppm in 2100.
  - The B1 scenario ["lower emissions"] projects a relatively rapid transition to a service and information economy, and an emphasis on the development of clean, non-fossil technology, resulting in an atmospheric concentration of ~550 ppm CO<sub>2</sub> by 2100.

- We compared future scenarios at mid-century (2020-2049) and end-of-century (2070-2099) to historical data from meteorological stations during a reference period (1961-1990)**, averaged by county (n= 3-5 stations per county). For more information on climate models, downscaling techniques, and emissions scenarios used, see Hayhoe et al. (2004) and related supplements.

### Grape Phenology and Quality

- We estimated grape ripening using accumulated growing degree-days (GDD) above 10°C from April to October (Amerine and Winkler, 1944), assuming ripening occurs between 1150-1300 GDD.

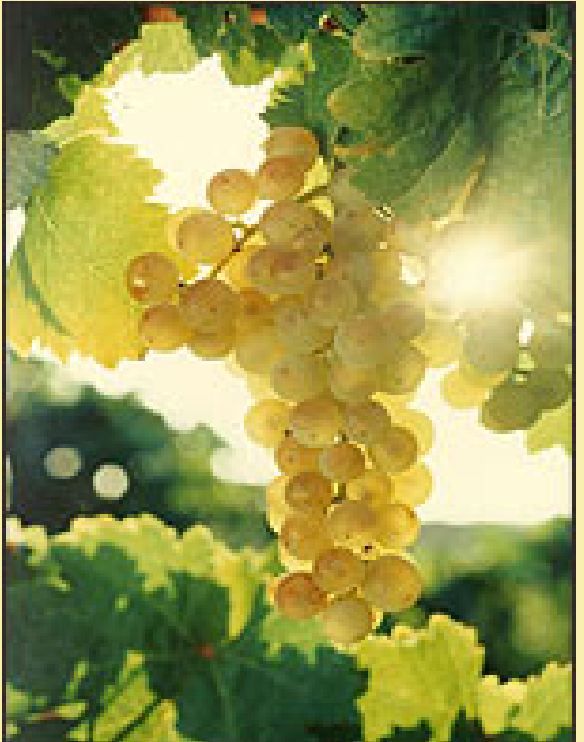
- These ripening estimates include the range of the top 5 wine grape varieties in California (Chardonnay, Cabernet Sauvignon, Zinfandel, Colombard, and Merlot), which account for more than 50% of the annual crush (Gladstones, 1992; CDFA, 2004).

- Quality may be defined by expert ratings, price, or chemical characteristics of the grapes or wine. Here we used the monthly average temperature at the time of ripening as an estimate of potential impact of temperature on grape quality, where an average temperature between 15°C and 22°C allows the accumulation of sugars to be balanced by appropriate declines in acid levels, and an average monthly temperature exceeding 24°C nearly always reduces quality for most table wines (Gladstones, 1992). This is a "floor" to establish a baseline ability to produce grapes consistent with the expression of desired variety characteristics, not a guarantee of achieving quality.

- Based on our definition of potential quality, we defined county-wide average climatic categories of optimal, marginal, and impaired for for producing high-quality winegrapes. Optimal classification means there are many places where high-quality vineyards can thrive. In marginal conditions, acceptable sites will be rarer and 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.

### Earlier ripening

### Generally suited for cooler sites



### Later ripening

### Generally suited for warmer sites

Chardonnay -> Zinfandel -> Merlot -> Colombard -> Cabernet Sauvignon

(data from Christensen et al., 2003)

## Results

### Mid-Century

- 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 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- 3.1°C relative to the baseline, depending on model and emissions scenario. .

- 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.

### End-Century

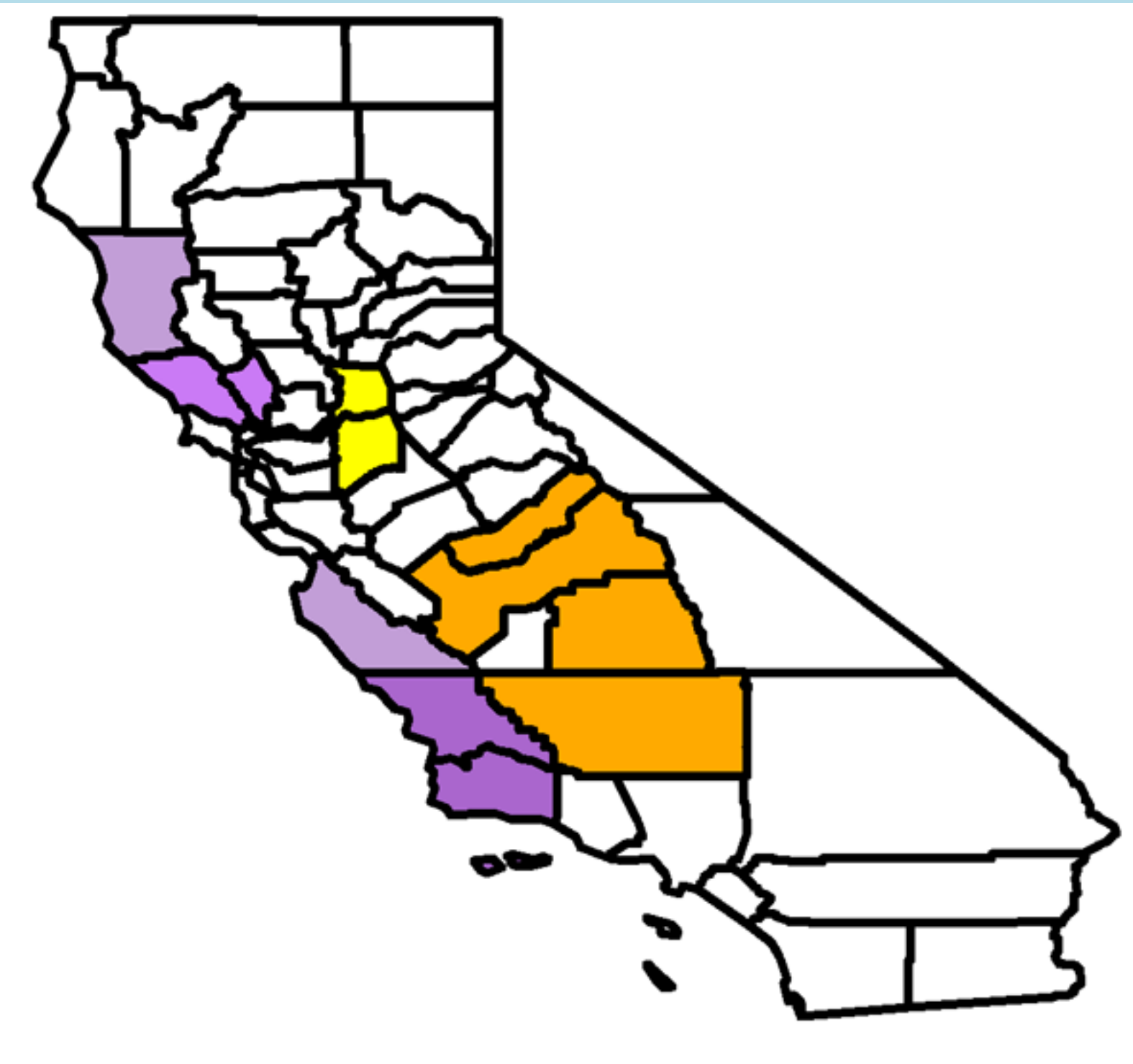
- For the end of century time period, the timing of grape harvest is expected to be an average of 1–2 months earlier relative to the reference period, with harvest occurring at higher temperatures. This produces a shift from optimal to marginal and marginal to quality-impaired ripening temperatures across major grape-growing 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.(Average statewide summer temperature increase: 2.15-4.6°C).
  - Under the higher A1fi emissions scenario, all locations are impaired under the HadCM3 climate model (with an average statewide summer temperature increase of 8.3°C). 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. (Average statewide summer temperature increase: 4.1°C).

## Discusson

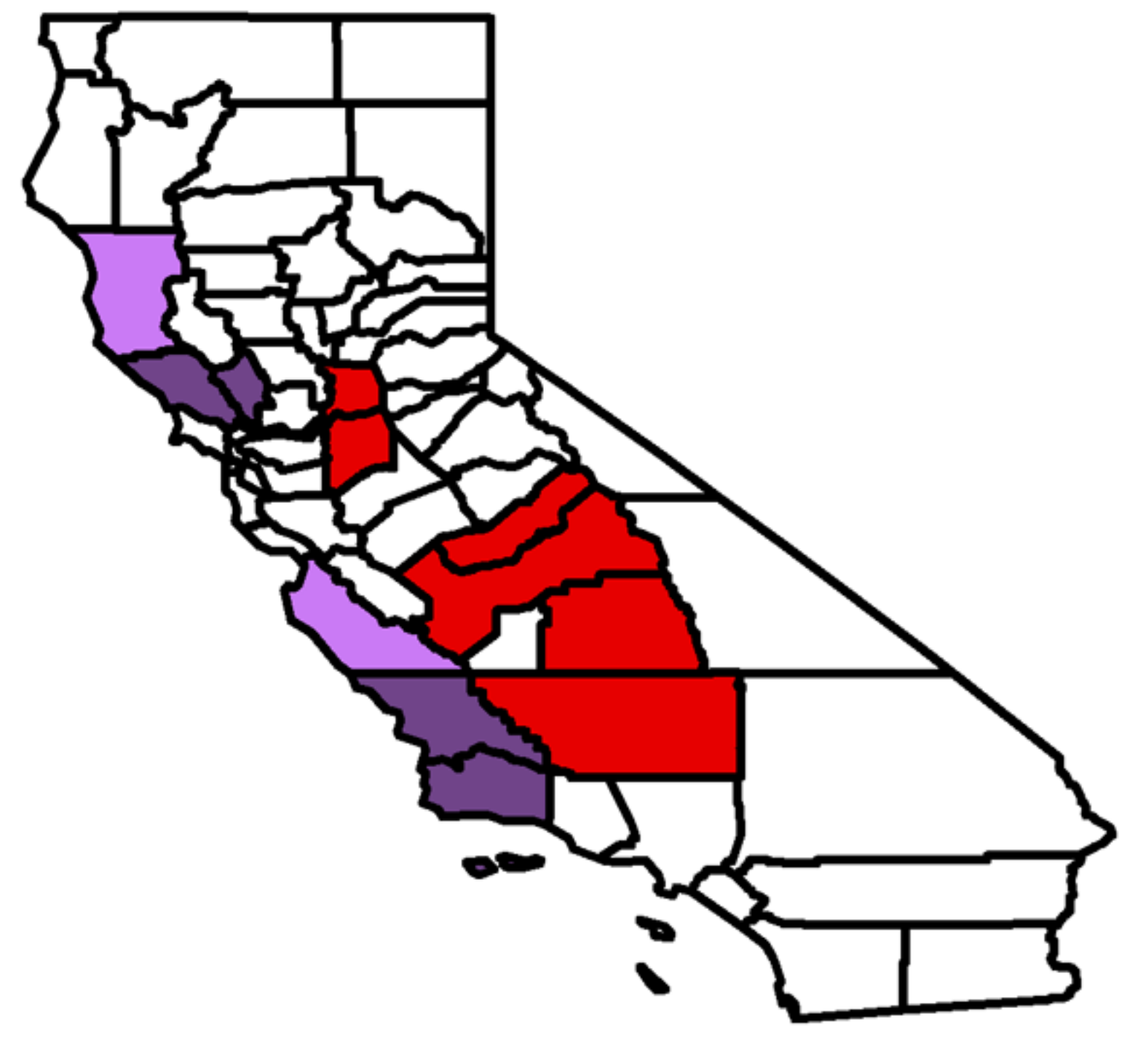
- While climate is a critical determinant of grape quality, clearly it does not prevent grapes from being grown outside of their preferred limits. Much of the Central Valley is already too warm to produce high-quality examples of popular varieties, and yet cool-suited Chardonnay is produced in hot Fresno County for an average of \$201/ton (vs. \$2316/ton in Napa) (CDFA, 2004) because there is a market for the familiar and popular grape.
- Grapegrowing may foster extensive connections with particular places, where a combination of environmental factors and cultural knowledge produces superior wines. This study did not examine the potential for areas not currently in viticulture to become better suited for grape cultivation, but competing pressures for land use in California and locally-based cultural values and expertise may make it difficult to shift high-quality grapegrowing areas rapidly. However, changes in varieties and planting locations may be needed, which would require significant investments of time and capital.

**References:** Amerine, MA and AJ Winkler. 1944. Composition and quality of musts and wines of California grapes. Hilgardia 15 (4): 493-673. • Berry, E. 1990. The importance of soil in fine wine production. Journal of Wine Research 1(2): 179-195. • California Agricultural Statistical Service (CASS). 2002. California Agricultural Statistics Review. Sacramento, CA. • California Department of Food and Agriculture (CDFA). 2004. Final grape crush report- 2003 crop. Sacramento, CA. • Christensen, LP, NK Dokoozlian, MA Walker, et al. 2003. Wine Grape Varieties in California. University of California Agriculture and Natural Resources Publication 3419. Oakland, CA. 188pp. • Hayhoe, K, D Cayan, CB Field, et al. 2004. Emissions pathways, climate change, and impacts on California. PNAS 101 (34): 12422-12427. • Gladstones, J. 1992. Viticulture and Environment. Winetitles, Underdale, South Australia. 310 pp. • Jones, GV. 2003. Winegrape phenology. p. 523-539 in Phenology: An integrative environmental science. MD Schwartz, ed. Kluwer Academic Publishers: Dordrecht. • MKF Consultants. 2004. Economic impact of California wine 2004. Wine Institute/California Association of Winegrape Growers, San Francisco, CA. 81pp. • Nakicenovic, N, J Alcamo, G Davis, et al. 2000. Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Cambridge University Press, New York). • Nemani, RR, MA White, DR Cayan, et al. 2001. Asymmetric warming over coastal California and its impact on the premium wine industry. Climatic Research 19: 25-34.

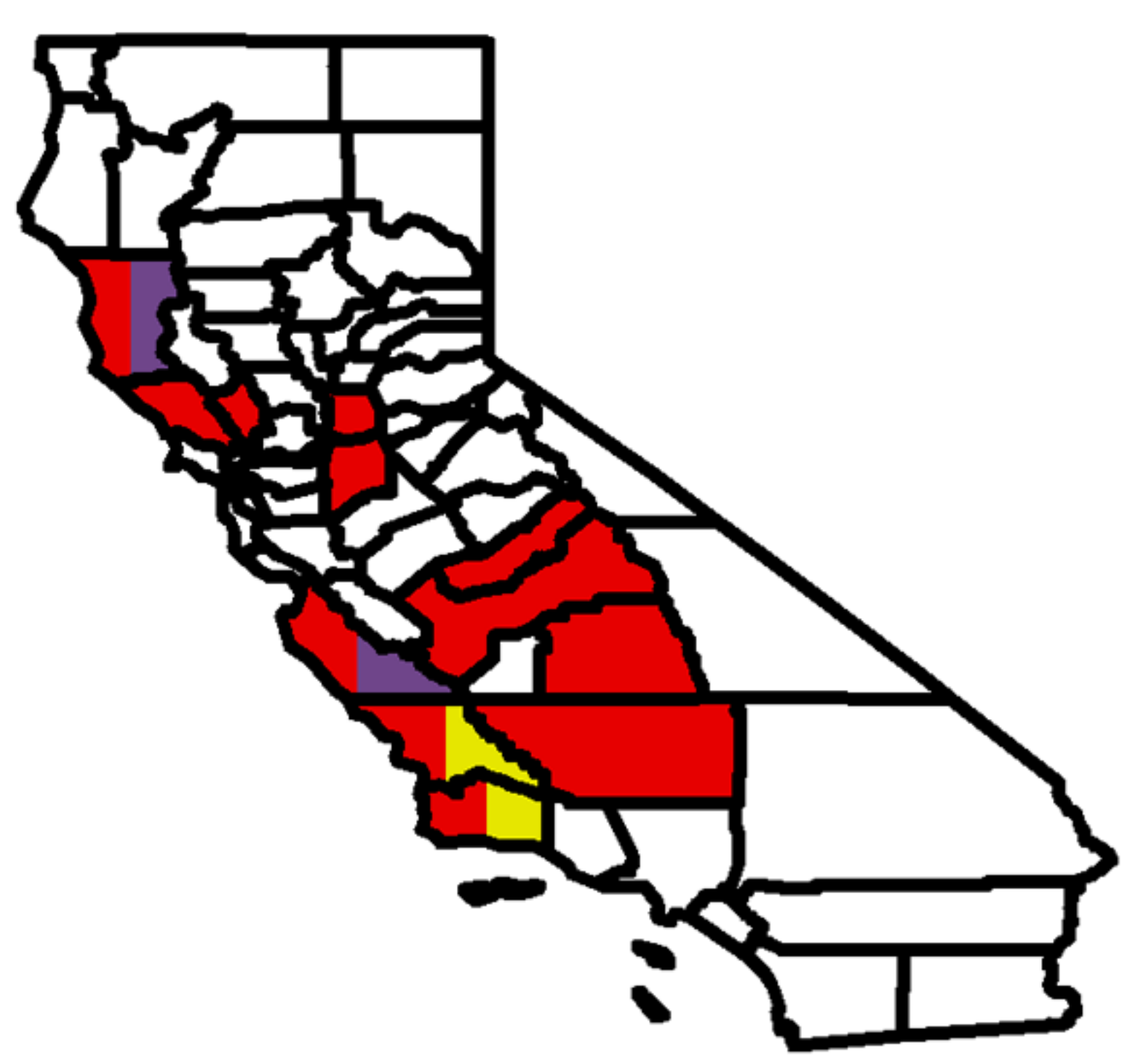
Baseline (1961-1990)



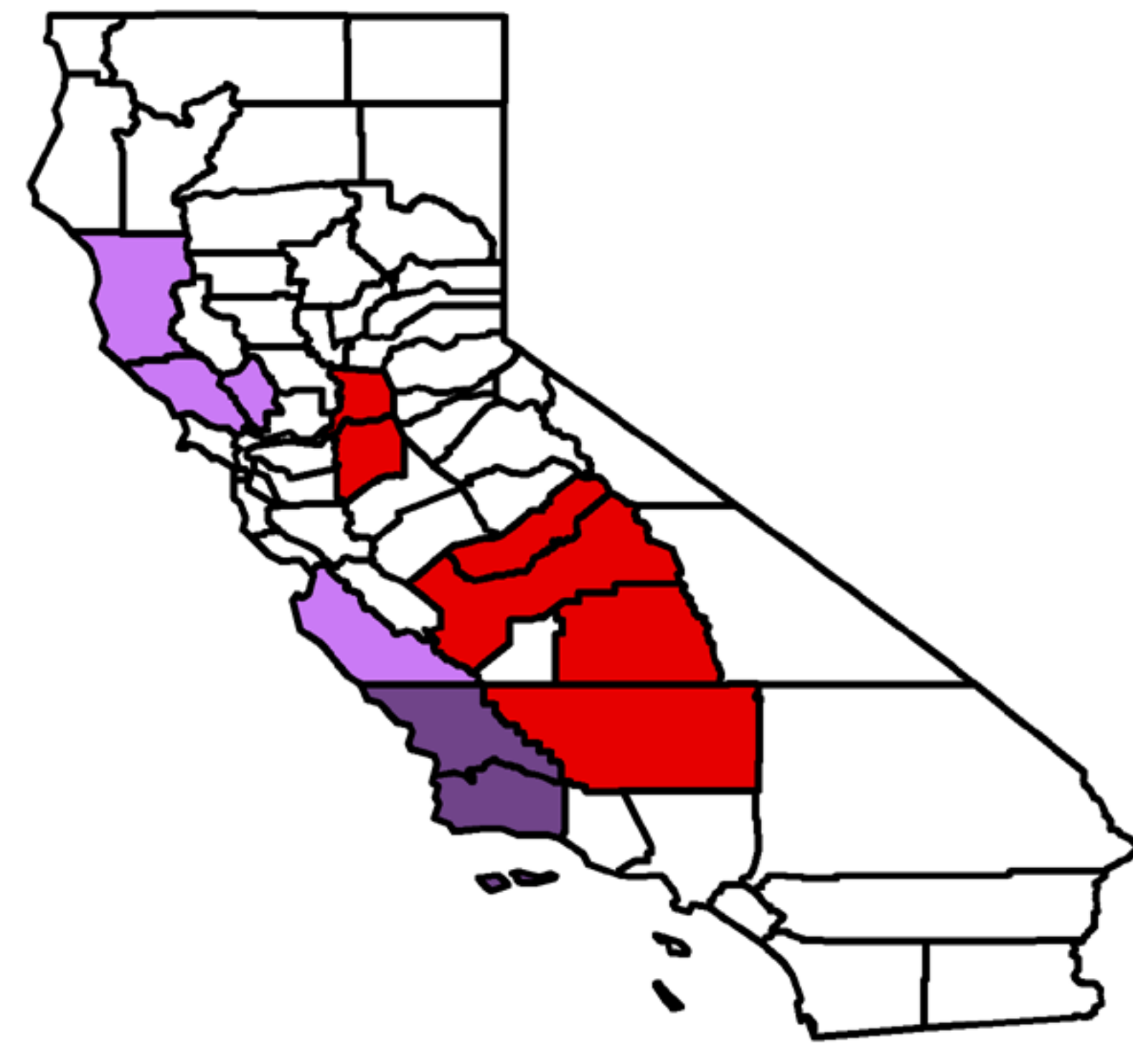
Mid-century, higher emissions (2020-2049, A1fi)



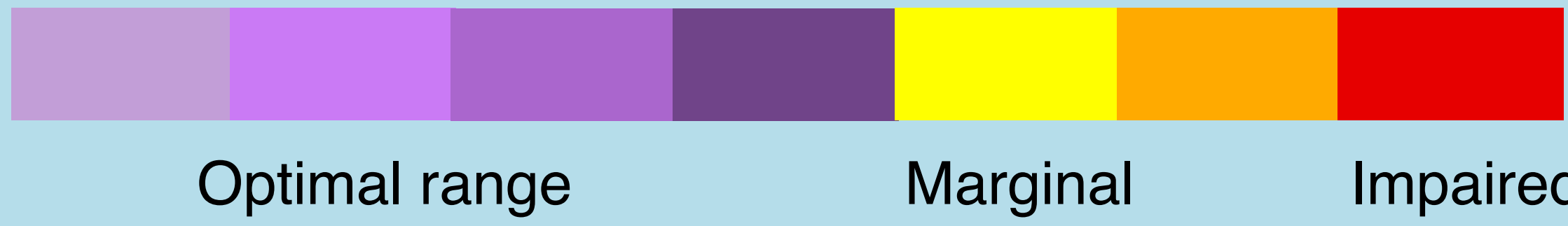
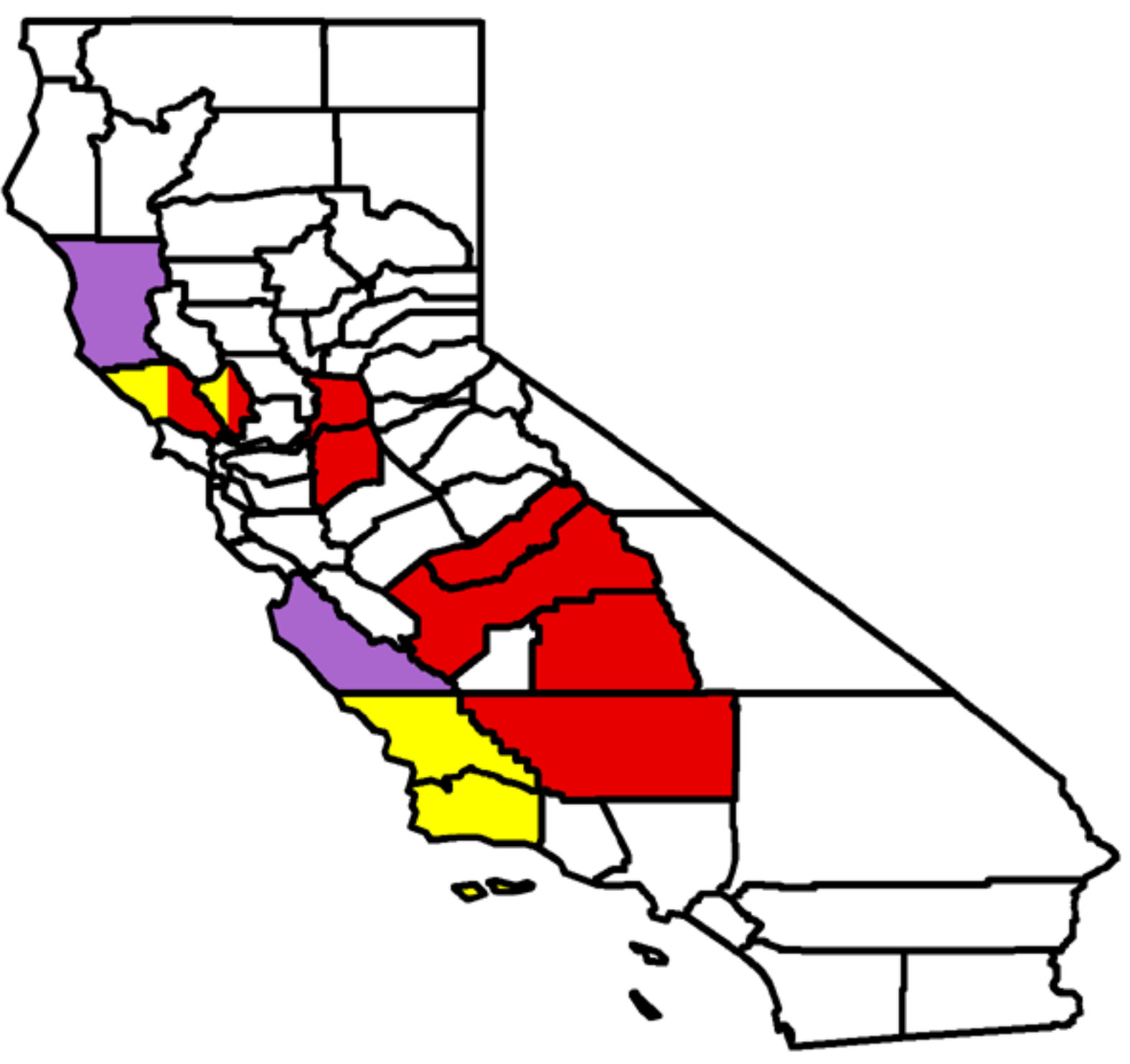
End-century, higher emissions (2070-2099, A1fi)



Mid-century, lower emissions (2020-2049, B1)



End-century, lower emissions (2070-2099, B1)



Agreement between the two climate models was strong for mid-century projections. Differences between models for the end-of-century timeframe are represented by split coloration by county, with the HadCM3 projections at left and PCM at right.

## Conclusions

- These results suggest significant potential impacts of modeled temperature increases for high-quality grape-growing regions throughout California.
- Climatic conditions for high-quality grapegrowing in California are roughly similar under higher and lower emissions scenarios at 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 at the end of the century, when retaining some areas of optimal high-quality grapegrowing conditions are more likely under the lower emissions scenario.
- Further study is underway to expand and improve this analysis. Efforts are aimed at incorporating: more detailed measures of temperature (timing and duration of daily and seasonal maxima and minima, and including requirements for effective chilling to set latent primary buds); greater detail within regions (perhaps by designated Viticultural Area); more specific information on the location and climatic responses of different varieties; incorporation of more quantiative measures of quality; and correlations of past climate variability with observed grape phenology and quality.