

## Climate adaptation wedges: a case study of premium wine in the western United States

To cite this article: Noah S Diffenbaugh *et al* 2011 *Environ. Res. Lett.* **6** 024024

View the [article online](#) for updates and enhancements.

### Related content

- [Global warming presents new challenges for maize pest management](#)  
Noah S Diffenbaugh, Christian H Krupke, Michael A White *et al.*
- [Agroclimatic potential across central Siberia in an altered twenty-first century](#)  
N M Tchebakova, E I Parfenova, G I Lysanova *et al.*
- [A need for planned adaptation to climate change in the wine industry](#)  
Marc J Metzger and Mark D A Rounsevell

### Recent citations

- [Precipitation intensity under a warming climate is threatening some Italian premium wines](#)  
Piero Di Carlo *et al*
- [Specialty fruit production in the Pacific Northwest: adaptation strategies for a changing climate](#)  
Laurie Houston *et al*
- [The future potential for wine production in Scotland under high-end climate change](#)  
Miriam Dunn *et al*

# Climate adaptation wedges: a case study of premium wine in the western United States

Noah S Diffenbaugh<sup>1,2,6</sup>, Michael A White<sup>3</sup>, Gregory V Jones<sup>4</sup> and Moetasim Ashfaq<sup>1,2,5</sup>

<sup>1</sup> Woods Institute for the Environment and Department of Environmental Earth System Science, Stanford University, Stanford, CA, USA

<sup>2</sup> Purdue Climate Change Research Center and Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN, USA

<sup>3</sup> Watershed Sciences, Utah State University, Logan, UT, USA

<sup>4</sup> Department of Environmental Studies, Southern Oregon University, Ashland, OR, USA

<sup>5</sup> Oak Ridge National Laboratory, Oak Ridge, TN, USA

E-mail: [diffenbaugh@stanford.edu](mailto:diffenbaugh@stanford.edu)

Received 9 February 2011

Accepted for publication 6 June 2011

Published 30 June 2011

Online at [stacks.iop.org/ERL/6/024024](http://stacks.iop.org/ERL/6/024024)

## Abstract

Design and implementation of effective climate change adaptation activities requires quantitative assessment of the impacts that are likely to occur without adaptation, as well as the fraction of impact that can be avoided through each activity. Here we present a quantitative framework inspired by the greenhouse gas stabilization wedges of Pacala and Socolow. In our proposed framework, the damage avoided by each adaptation activity creates an 'adaptation wedge' relative to the loss that would occur without that adaptation activity. We use premium winegrape suitability in the western United States as an illustrative case study, focusing on the near-term period that covers the years 2000–39. We find that the projected warming over this period results in the loss of suitable winegrape area throughout much of California, including most counties in the high-value North Coast and Central Coast regions. However, in quantifying adaptation wedges for individual high-value counties, we find that a large adaptation wedge can be captured by increasing the severe heat tolerance, including elimination of the 50% loss projected by the end of the 2030–9 period in the North Coast region, and reduction of the projected loss in the Central Coast region from 30% to less than 15%. Increased severe heat tolerance can capture an even larger adaptation wedge in the Pacific Northwest, including conversion of a projected loss of more than 30% in the Columbia Valley region of Washington to a projected gain of more than 150%. We also find that warming projected over the near-term decades has the potential to alter the quality of winegrapes produced in the western US, and we discuss potential actions that could create adaptation wedges given these potential changes in quality. While the present effort represents an initial exploration of one aspect of one industry, the climate adaptation wedge framework could be used to quantitatively evaluate the opportunities and limits of climate adaptation within and across a broad range of natural and human systems.

**Keywords:** climate change, adaptation, vulnerability, RegCM3, viticulture

---

<sup>6</sup> Address for correspondence: Department of Environmental Earth System Science, Stanford University, 473 Via Ortega, Stanford, CA 94305-4216, USA.

## 1. Introduction

Although governments continue to consider policies to constrain the level of greenhouse gas (GHG) concentrations in the atmosphere (e.g., [1, 2]), it is becoming increasingly clear that some adaptation to climate change will be required in the coming decades. The expected need for adaptation arises in part from the recognition that inertia in the climate system is likely to create continued climate change after GHG stabilization (e.g., [3–6]). Further, policy negotiations are focused on GHG levels that guarantee further global warming (e.g., [1, 2, 7]). While these targets are relatively moderate compared to unconstrained warming [8], they are not likely to avoid high-impact regional and local climate change [9–11].

Climate adaptation activities can be passive or active [12, 13]. Passive adaptation activities include stimulating economic growth (e.g., [13, 14]). Active adaptation activities include building general resilience to environmental stress [15] (such as strengthening social networks [16, 17] or liberalizing trade policies [18]), optimizing institutions and practices for anticipated changes in climate [12] (such as altering water-resource-management or seed-breeding strategies), and creating novel climate-targeted institutions and practices (such as the UNFCCC Adaptation Fund [19] and associated entities [20, 21]).

Design and implementation of effective adaptation activities requires quantification of the possible impacts of climate change, and the sensitivity of those impacts to different adaptation activities. The damage avoided by each activity creates a ‘wedge’ relative to the loss that would occur without that activity (figure 1). These wedges are analogous to the GHG stabilization wedges of Pacala and Socolow [22], and can be summed to quantify the total benefit relative to non-adapted impacts. The effects of various adaptation activities are likely to vary with changes in climatic and socioeconomic conditions [12, 13, 16–18], and can be quantified within the context of unconstrained climate change, GHG mitigation policies, or the current climate (figure 1).

We use premium winegrape cultivation to illustrate the climate adaptation wedge framework. As summarized by White *et al* [23], a number of features make premium wine a compelling study of potential climate change impacts, including broad and intense economic and cultural importance, extensive analyses of climate influence on winegrape productivity and quality, and reliance on a narrow climate envelope for the highest-value production. In addition, although wine quality is a product of terroir, which also includes important influences of geological substrate and cultural practice [24], variations in climate within that narrow envelope strongly influence variations in wine quality and value (e.g., [23, 25]). Further, winegrape physiology is sensitive to excessive occurrence of both severe heat and severe cold [23], creating the potential for competing impacts from projected warming.

Here we evaluate temperature suitability in the western United States (US), with emphasis on the near-term period that covers the years 2000–39. Almost all of the US premium wine production and value are concentrated in the western

US, with California accounting for 89.25% of the total US production, and Washington and Oregon ranking third and fourth in State production, respectively [26]. The California industry alone has substantial economic impact, including \$51.8 billion and \$125.3 billion on the California and US economies, respectively, in 2005 [27].

The potential for relatively moderate mean warming over the near-term decades [8, 28] is of particular importance for the suitability of premium winegrape cultivation in the western US. On the one hand, the temperature regime in the high-value areas of California is near optimal at present [25, 29], so any substantive change in those areas could be expected to have negative consequences. Recent temperature changes have already impacted grapevine phenology and wine quality [25, 30, 31], and further temperature changes are likely to occur over the next three decades [28], including substantial intensification of severe hot events [9]. On the other hand, large areas of the western US are currently cold-limited, suggesting that warming could provide some benefit [30], particularly if the positive effects of decreasing cold limitation outpace the negative effects of increasing hot limitation over the near-term decades.

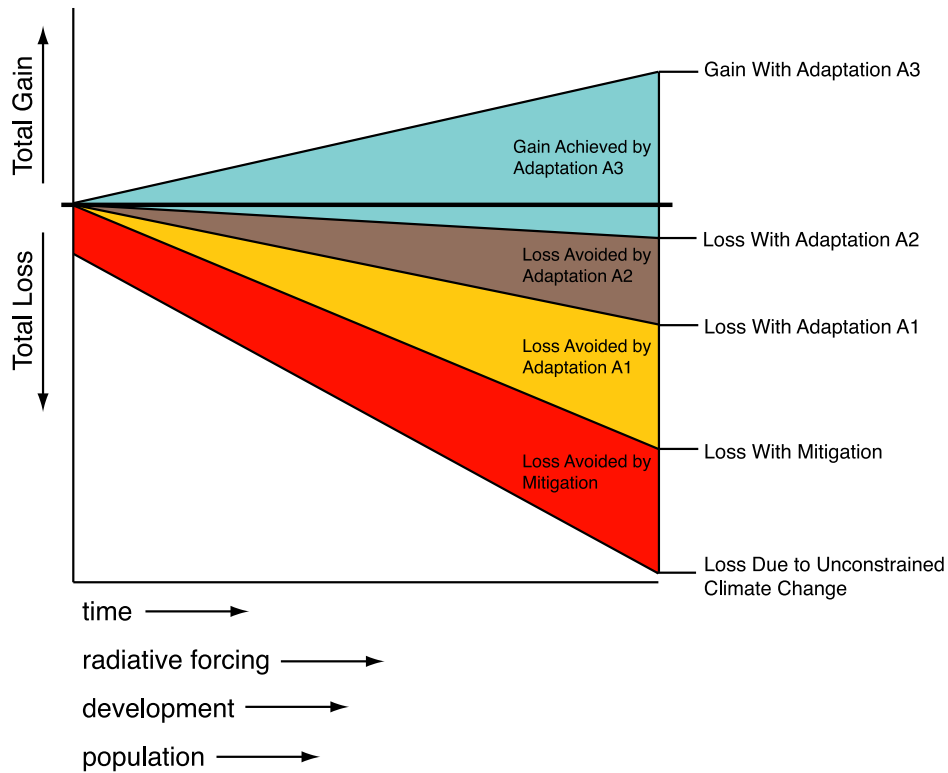
The range of temperature tolerances exhibited at present, combined with the possibility of both positive and negative impacts of climate change, make premium winegrape cultivation an attractive testbed for the climate adaptation wedge framework. In this initial study, we explore that framework by quantifying the impacts of near-term warming on thermal suitability in the western US, and the sensitivity of those impacts to varying levels of temperature tolerance.

## 2. Methods

### 2.1. Climate model experiment

We employ a high-resolution nested climate model [32] in order to capture the spatial heterogeneity of temperature and temperature extremes that can be critical for premium winegrape suitability (e.g., [23, 25]; table 1). We use the five-member RegCM3 ensemble experiment described in [9], which covers the period from 1950 to 2039 in the SRES A1B emissions scenario [33]. The experiment uses the RegCM3 grid of [34], which covers the full continental US with 25 km resolution in the horizontal, and is nested within five realizations of the NCAR CCSM3 atmosphere–ocean GCM [35]. The CCSM3 simulations are described in [36].

We correct errors in the RegCM3-simulated temperatures using the quantile-based bias-correction method of Ashfaq *et al* [37, 38]. The method corrects the errors in each quantile of each of the calendar months, yielding a daily-scale maximum and minimum temperature time series that both preserves the simulated change in monthly- and daily-scale temperature at each grid point and substantially improves the RegCM3-simulated seasonal- and daily-scale temperature fields [37]. As in [37], we apply the bias correction using the monthly-mean daily maximum and minimum observational temperature data from the PRISM project [39]. We first interpolate the RegCM3 and PRISM data to a common 1/8-degree geographical grid, and then perform the climate model



**Figure 1.** Conceptual illustration of the climate adaptation wedges framework. The magnitude of loss or gain due to climate change varies with time, radiative forcing, economic development, population, etc, and with different mitigation and adaptation measures.

**Table 1.** Descriptive statistics for the number of days during the growing season with maximum temperatures greater than 35 °C for ten western United States wine regions from 1948 to 2004. The values are averages over multiple stations in each region, obtained from the United States Historical Climatology Network (see [67, 25] for further details). The growing season is calculated as 1 April through 31 October.

Region	Growing season days >35 °C			
	Mean	Std. dev.	Max	Min
Puget Sound	2.0	1.9	6	0
Willamette Valley	4.9	3.6	14	0
Umpqua Valley	7.8	4.3	20	0
Rogue Valley	17.5	8.4	38	1
Columbia Valley, WA	17.9	7.6	33	4
Columbia Valley, OR	12.5	6.0	26	3
North Coast	20.4	5.9	34	8
Central Coast	20.1	4.8	32	12
North Valley	46.6	9.6	66	23
Central Valley	68.4	10.0	93	46

bias-correction and temperature screening analyses on this 1/8-degree grid. Because we analyze the 40 year period from 2000 through 2039, we base the bias correction on the 40 year historic period from 1960 through 1999. Given the five-member ensemble, each 10 year period contains 50 simulated years.

**2.2. Climate suitability for growing grapes for premium wine production**

A number of approaches have been taken to assess the potential impacts of climate change on the premium wine industry

in the US (e.g., [23, 40–42]). We follow the temperature suitability screening of White *et al* [23]. These criteria are based on observed relationships between temperature and winegrape production, and are designed to identify the temperature suitability associated with the upper quartile of price within a given category. The screening is based on the growing degree day (GDD) criteria of Winkler [43, 44], combined with additional seasonal- and daily-scale threshold criteria, as summarized in table 2. A grid point that meets all temperature criteria during a given year is determined to be thermally suitable for growing grapes for premium wine production during that year. We note that this approach is an approximation based on empirical relationships with temperature, and that certain varieties and management strategies will allow for premium wine production outside of these bounds [24].

The Winkler GDD summation provides both a broad temperature suitability criterion and quantification of the suitability for different grape varieties and wine styles within that broad criterion. Using GDD above 10 °C, Winkler *et al* [43] defined five classes of viticultural suitability based upon the style and quality of wine that could be produced in a given climate. In Region I climates (1111–1390 GDD), early ripening varieties achieve high quality. For Region II (1391–1670 GDD), most early and mid-season table wine varieties will produce good quality wines with light to medium body and good balance. Region III (1671–1950 GDD) is a favorable climate for high production of standard to good quality full-bodied dry to sweet table wines. Region IV (1951–2220 GDD) is favorable for high production, but table

**Table 2.** Temperature screening criteria.

Temperature variable	Minimum allowable	Maximum allowable
Growing season <sup>a</sup> growing degree days (GDD) <sup>b</sup>	850 GDD	2700 GDD
Growing season <sup>a</sup> diurnal temperature range (DTR)	—	20 °C
Ripening season <sup>c</sup> diurnal temperature range (DTR)	—	20 °C
Fall <sup>d</sup> , winter <sup>e</sup> and spring <sup>f</sup> severe cold days <sup>g</sup>	—	14 days
Growing season <sup>a</sup> severe hot days <sup>h</sup>	—	15–45 days
Growing season <sup>a</sup> mean temperature	13 °C	20–22 °C

<sup>a</sup> 1 April to 31 October. <sup>b</sup> 15 August to 15 October. <sup>c</sup> Base 10 °C. <sup>d</sup> 1 September to 30 November.

<sup>e</sup> 1 December to 28 February. <sup>f</sup> 1 March to 31 May.

<sup>g</sup> Total of fall days below  $-6.7$  °C, Winter days below  $-12.2$  °C, and Spring days below  $-6.7$  °C.

<sup>h</sup> Days above 35 °C.

wine quality will be acceptable at best. Region V (2221–2499 GDD) typically makes low-quality bulk table wines or fortified wines, or is best for table grape varieties destined for early season consumption. (The above GDD thresholds follow White *et al* [23].) In addition, the recent re-analysis of GDD over the western US by Jones *et al* [29] identified the upper and lower thresholds for Winkler regions I and V, which were not previously defined [43]. We therefore also allow for a Winkler Ia class that varies from 850 to 1110 GDD (which corresponds to hybrid and very early cool climate varieties), and a Winkler Va class that varies from 2500 to 2700 GDD.

Temperature change over the near-term decades could create adaptation pressure by causing a given location to move from one Winkler category to another. In addition, temperature change could alter the frequency with which the other temperature screening thresholds (table 2) are exceeded in a given location. Because warming would be expected to increase the pressure from hot limits and decrease the pressure from cold limits, we test the potential for increased tolerance of hot conditions to reduce the loss of suitable area. For the growing season temperature criterion, we first test the upper limit of 20 °C used by White *et al* [23]. In addition, Jones *et al* [29] identified a hot limit of 21 °C for premium wines in the region, and established that the range of 21–24 °C is currently associated with bulk wine, table grapes and raisins [29]. We therefore also allow for extended upper limits of 21 and 22 °C in order to test the possible need for adaptation at and above the current growing season hot threshold. Similarly, given the strong sensitivity to severe heat found in the study of White *et al* [23], and the recognition that different areas within the western US exhibit a range of severe heat tolerances at present (table 1), we test severe heat tolerances of 15, 30, and 45 growing season hot days.

### 3. Results

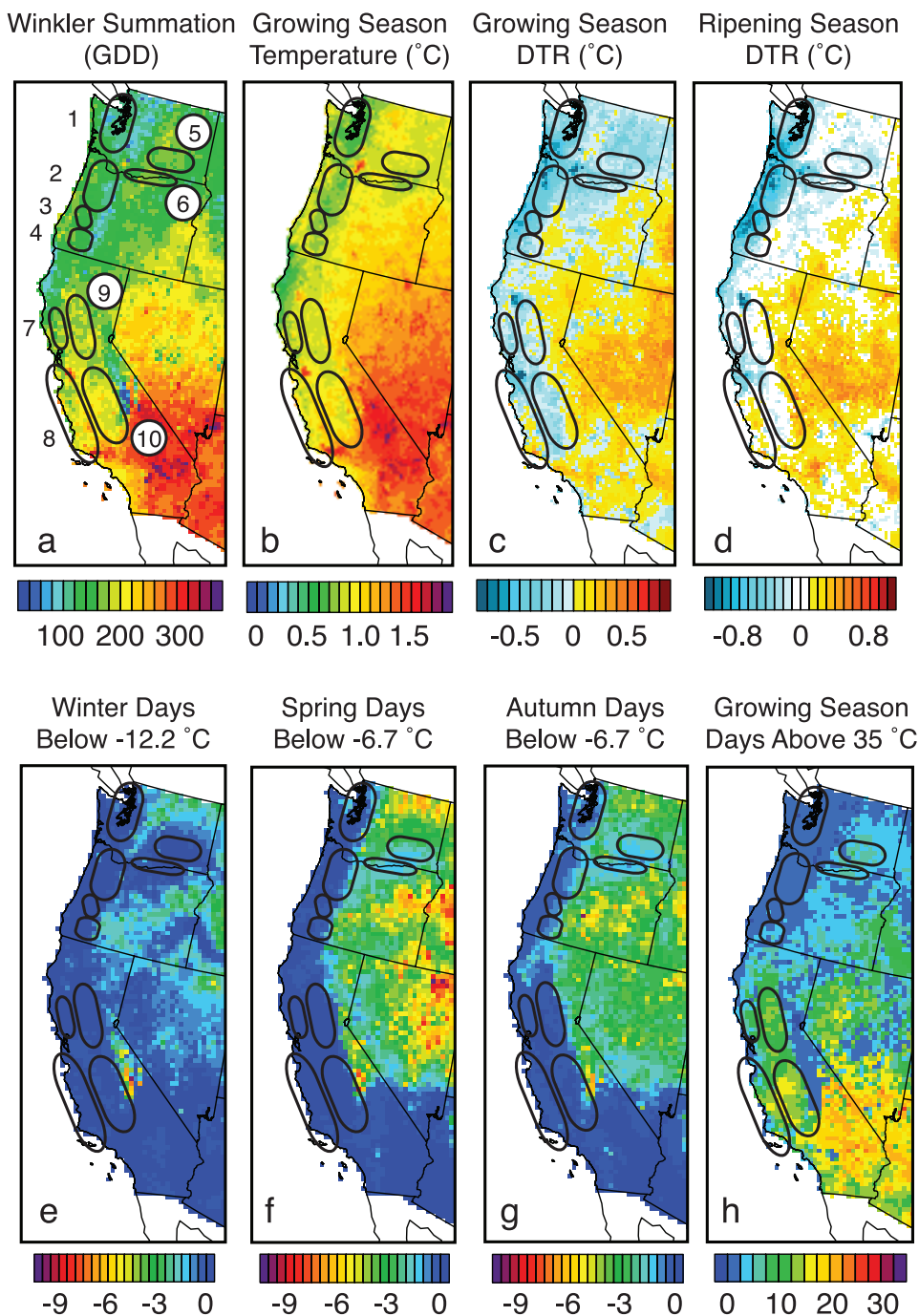
Here we focus on the States of California, Oregon and Washington, with particular emphasis on the high-value Central Coast, North Coast, Willamette Valley and Columbia Valley growing areas analyzed in the study of Jones and Goodrich [25] (see areas and counties delineated in figures 2 and 3). Growing season heat accumulation is projected to increase in all three states over the 2000–39 period, with ensemble-mean increases (2030–9 minus 2000–9) ranging

from 140 to 340 GDD in the Central Coast of California, from 60 to 220 GDD in the North Coast of California, and from 100 to 200 GDD in the Willamette Valley of Oregon and the Columbia Valley of Washington and Oregon (figure 2(a)). Similarly, mean growing season temperature is projected to increase 0.6–1.7 °C in the Central Coast, 0.5–1.1 °C in the North Coast, 0.6–0.7 °C in the Willamette Valley, and 0.7–1.0 °C in the Columbia Valley (figure 2(b)). The number of growing season days with maximum temperature above 35 °C is projected to increase by up to 17.5 days in the Central Coast, up to 10 days in the North Coast, and up to 7.5 days in the Columbia Valley (figure 2(h)). Further, the number of spring (autumn) days with minimum temperature below  $-6.7$  °C is projected to decrease by up to  $-6.0$  ( $-5.0$ ) days in the Columbia Valley (figures 2(f) and (g)).

The area that meets the GDD criterion but does not meet the severe temperature criterion is projected to increase in many counties in the 2030–9 period relative to the 2000–9 period (figure 3). For example, for a threshold of 15 days, up to 30% of the Winkler area in Santa Barbara County (Central Coast) is lost to severe hot days in the 2000–9 period (figure 3(a)), while up to 50% is lost in the 2030–9 period (figure 3(f)). However, the number of counties that exhibit enhanced loss of Winkler area in the 2030–9 period is greater with a severe hot threshold of 15 days than with a threshold of 45 days (figures 3(f)–(g)), and tolerance of 45 days eliminates most loss of Winkler area in the majority of counties in the Columbia Valley, Willamette Valley, North Coast and Central Coast regions (figures 3(a)–(g)). Likewise, warming in the early 21st century increases the fraction of Winkler area that is lost to high mean growing season temperature in the North and Central Coast regions, including from 50% to 70% in Napa County (North Coast) and from 10% to 30% in Santa Barbara County (Central Coast) (figures 3(c) and 4(h)). Enhancing tolerance from 20 to 21 °C decreases the loss of Winkler area in both the 2000–9 and 2030–9 periods, and negates the warming-induced loss of Winkler area relative to a 20 °C baseline (figures 3(c), (d), (h) and (i)).

The sensitivity to temperature tolerance can be used to quantify a set of climate adaptation wedges for each county (figure 4). For illustrative purposes, we focus on four high-value counties in the western US that represent a range of current climates (e.g., [25]; table 1). In Santa Barbara County (Central Coast), increasing tolerance of maximum growing season temperature from 20 to 22 °C reduces the loss by

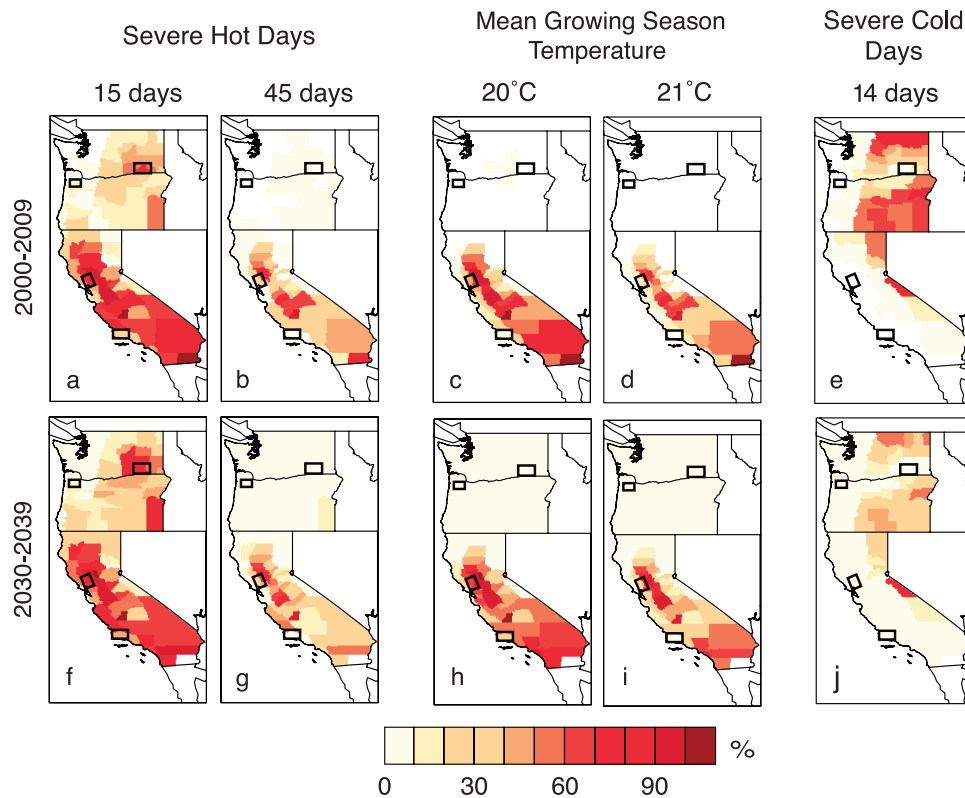




**Figure 2.** Change in temperature suitability variables (2030–9 minus 2000–9). The variables are described in table 2. Each decadal period contains 10 simulated years from each of the five ensemble members, yielding a total of 50 simulated years in each decadal period. ‘GDD’ is growing degree days. ‘DTR’ is diurnal temperature range. The ellipses indicate the regions identified in [25], which are reported in table 1 and mentioned in the text. The regions are: 1 = Puget Sound; 2 = Willamette Valley; 3 = Umpqua Valley; 4 = Rogue Valley; 5 = Columbia Valley (WA); 6 = Columbia Valley (OR); 7 = North Coast; 8 = Central Coast; 9 = North Valley; 10 = Central Valley.

the end of the 2030–9 period from more than 30% to less than 25%. A larger wedge can be captured by increasing the severe heat tolerance from 15 days to 30 days, thereby reducing the area loss to less than 15% by the end of the 2030–9 period, and creating a gain prior to the mid-2020s. Tolerance to both 30 days and 22 °C creates gains over the full near-term period, although the positive effect decreases from 25% in the 2000–9 period to 10% in the 2030–9 period. In

Napa County (North Coast), increasing tolerance of maximum growing season temperature from 20 to 22 °C (with a severe heat tolerance of 15 days) has almost no affect on the area lost over the near-term decades, while increasing the tolerance of growing season hot days from 15 days to 30 days (with a growing season temperature tolerance of 20 °C) eliminates the loss by the end of the 2030–9 period. Tolerance of both 30 days and 22 °C creates a gain over the full near-term period,



**Figure 3.** Area in each county that is suitable in the Winkler growing degree day (GDD) criterion, but not suitable in the severe hot days, mean growing season temperature, and severe cold days criteria, expressed as a percentage of the area that is suitable in Winkler criterion. Each of the temperature variables is described in table 2. The severe hot days criterion is shown for two maximum thresholds: 15 days during the growing season and 45 days during the growing season. The mean growing season temperature criterion is shown for two maximum thresholds: mean growing season temperature of 20 °C and mean growing season temperature of 21 °C. The black rectangles in each panel highlight the four counties featured in the text: Walla Walla County (Columbia Valley, WA); Yamhill County (Willamette Valley); Napa County (North Coast); and Santa Barbara County (Central Coast).

including more than 50% in the 2030–9 period. In Walla Walla County (Columbia Valley), tolerance of 30 days and 20 °C results in a gain of more than 150% in the 2030–9 period (compared with a loss of more than 30% for a tolerance of 15 days and 20 °C), while increasing tolerance to 22 °C provides no additional gain. Finally, warming over the near-term decades results in a slight increase in area in Yamhill County (Willamette Valley) for tolerance of 15 days and 20 °C. Tolerance of 30 days increases the gain to more than 15% by the end of the 2030–9 period, although increasing tolerance to 45 days and/or 22 °C provides little additional benefit.

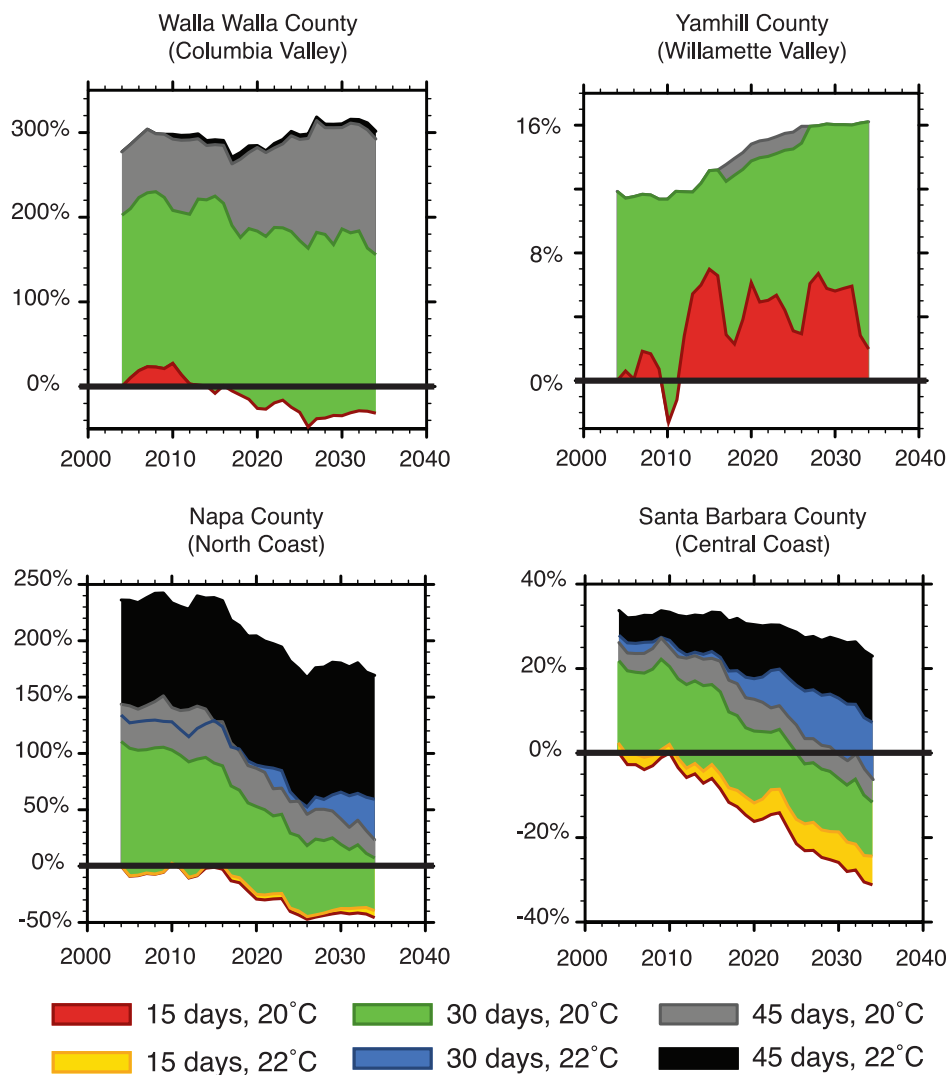
#### 4. Discussion

##### 4.1. Potential adaptation options

While it is not known whether the historical temperature relationships between temperature and wine quality will hold in a new climate, these relationships have been robust over many decades, including in the face of recent warming in the western US [25]. The potential changes in suitability in response to projected near-term warming therefore highlight the importance of societal ability to capitalize on adaptive capacity in existing systems, and to make longer-term changes that are optimized to a changing climate. Specific

adaptation strategies for growers/producers include planting in new locations, planting different varieties or clones, altering vineyard design and/or management, and adjusting winery processing [45–47].

For those that are able to consider new locations, areas that are higher in latitude, higher in elevation, and/or closer to the coast could potentially provide climates that would allow maintenance of style and quality [45]. For those that are not able to consider new locations, the relatively narrow climate suitability of each variety will likely cause even small changes in climate to require shifts to different varieties or newer, more heat tolerant clones of the same variety. Fortunately, *Vitis vinifera* has a wide genetic diversity that can enable such shifts [47]. However, within *Vitis vinifera*, there are few widely planted varieties that can produce quality wine in excessively warm climates [23] (figure 3). The rate of climate change and/or the rate at which variations in environmental tolerance can be exploited may therefore impose adaptability limits, particularly in long-lived systems such as premium wine, for which the long time to maturity (1–2 decades) and in-place lifetime (3–5 decades or more) increase the investment and opportunity costs of changes in location or variety, as well as the potential loss should the actual climate change be different than anticipated [46].



**Figure 4.** Area in four representative counties that is suitable in the full temperature suitability screening given varying maximum thresholds in the severe hot days and mean growing season temperature criteria. The temperature variables for the full suitability screening are described in table 2, and the representative counties are shown in figure 3. The area is expressed as a percentage change from the baseline area, which is calculated for the 2000–9 period from the five-member ensemble using a tolerance of 15 growing season hot days and maximum growing season temperature of 20 °C. For each color, the dark line shows the 10 year running mean of percentage change across the ensemble for a pair of maximum thresholds in the severe hot days and mean growing season temperature criteria (e.g., 30 days during the growing season and mean growing season temperature of 20 °C), while the light field shows the difference in area from the adjacent maximum threshold pair (represented by the adjacent dark line). The severe hot days criterion is shown for three maximum thresholds: 15 days during the growing season, 30 days during the growing season, and 45 days during the growing season. The mean growing season temperature criterion is shown for two maximum thresholds: mean growing season temperature of 20 °C and mean growing season temperature of 22 °C.

The adaptation wedge framework can help to quantify the adaptability gaps associated with these adaptability limits. For example, if—hypothetically—the maximum temperature tolerance that could be reached by growers in Santa Barbara County on a three-decade time horizon was 30 growing season hot days and maximum growing season temperature of 20 °C, then by the end of the 2030s there would still be a projected loss equaling approximately 10% of baseline area (figure 4). This 10% loss would represent the adaptability gap, which would either need to be closed by GHG mitigation actions, or incurred as a loss from climate change. The potential for both further warming [8, 28] and further adaptation as the century progresses means that such gaps could grow or shrink

with time, depending on the system, location, and rate and magnitude of both climate change and adaptation activity.

In addition, even in the absence of adaptability limits, adaptation to a new climate regime may have important impacts on quality and/or value that are at least partially independent of changes in total producible area. For example, although Napa County exhibits very little change in total Winkler suitability over the near-term decades (figure 5), substantial losses are projected in the high-quality Region III class. These projected losses are compensated by projected gains in the low-quality hot Region V and Va classes, suggesting a decrease in the overall quality and value of the producible area. Likewise, in Santa Barbara county, substantial



losses in the Region II and III classes are compensated by gains in the warm Region IV class and hot Region V class, while in Walla Walla County, substantial losses in the Region II class are offset by gains in the intermediate-to-warm Region III and IV classes. In contrast, in Yamhill County, losses in the very cool Region Ia class are offset by gains in the higher-quality Region II class, suggesting an increase in the overall quality and value of the producible area.

Adaptation options in response to these more subtle changes in temperature suitability are likely to vary depending on the local baseline climate. Near-term warming would provide the widest adaptation wedge for marginally cool areas, where more consistent vintage-to-vintage ripening, higher-quality potential, and a wider range of varieties could be realized. Alternatively, for areas that are already near the warm limit of temperature suitability, there are few large-scale adaptation measures that would ameliorate the pressure toward lower-quality, bulk wine production. For areas with intermediate climates, the adaptive capacity depends upon the nuances of the current suitability. For example, a wine producing area with a warm Region II climate at present would likely require relatively complex adaptation measures (e.g., new varieties and/or changes in vineyard structure). In contrast, a wine producing area with a cool Region II climate would have a wide range of relatively accessible adaptation measures that could maintain similar quality levels in the face of near-term warming (e.g., vine management).

The potential for adaptation actions that do not require changes in location and/or varieties highlights the importance of adaptation wedges that are associated with cultural practice. Indeed, for relatively small temperature changes, growers have tremendous adaptive capacity through alterations to the trellising system (to shade the vines through larger canopies), pruning style and timing (to increase the size of the canopy and/or delay growth), row orientation (to increase fruit protection from heat and/or sunburn), and irrigation management (if sufficient water is available). In addition, some adaptive capacity can also be realized in the winery, where greater control over fermentation, alcohol removal, and the ability to acidulate can—to some degree—maintain a current style and quality benchmark in response to changing winegrape quality. Further, there may also be adaptation potential through changes in marketing, which can strongly influence the public's perception of 'quality wine' [48–51]. However, although these marketing effects can strongly influence overall wine consumption (e.g., [49, 50]), the present climatic constraints of premium winegrape cultivation suggest that there are limits to the ability of marketing to offset changes in winegrape quality, particularly given that consumers are accustomed to particular traits of particular varieties. For example, pinot noir styles are presently enjoyed over a narrow range of delicate, finesse styles, and changes toward 'bigger and bolder' styles that might be expected to come from a warmer climate would fall well outside of what consumers have come to expect from that varietal.

The potential adaptation actions available to growers, producers and marketers would require different scales of investment, with changes in location, plantings (varieties or

clones), and vineyard infrastructure (row orientation) having the greatest financial impacts due to development costs and the time required to reach sustainable production levels. Further, decisions to adapt to climatic changes through growing, production or marketing practices will necessarily require a recognition of the nature of the impacts of climate change on the fruit that is produced, whether in advance of or in response to those impacts manifesting in the field.

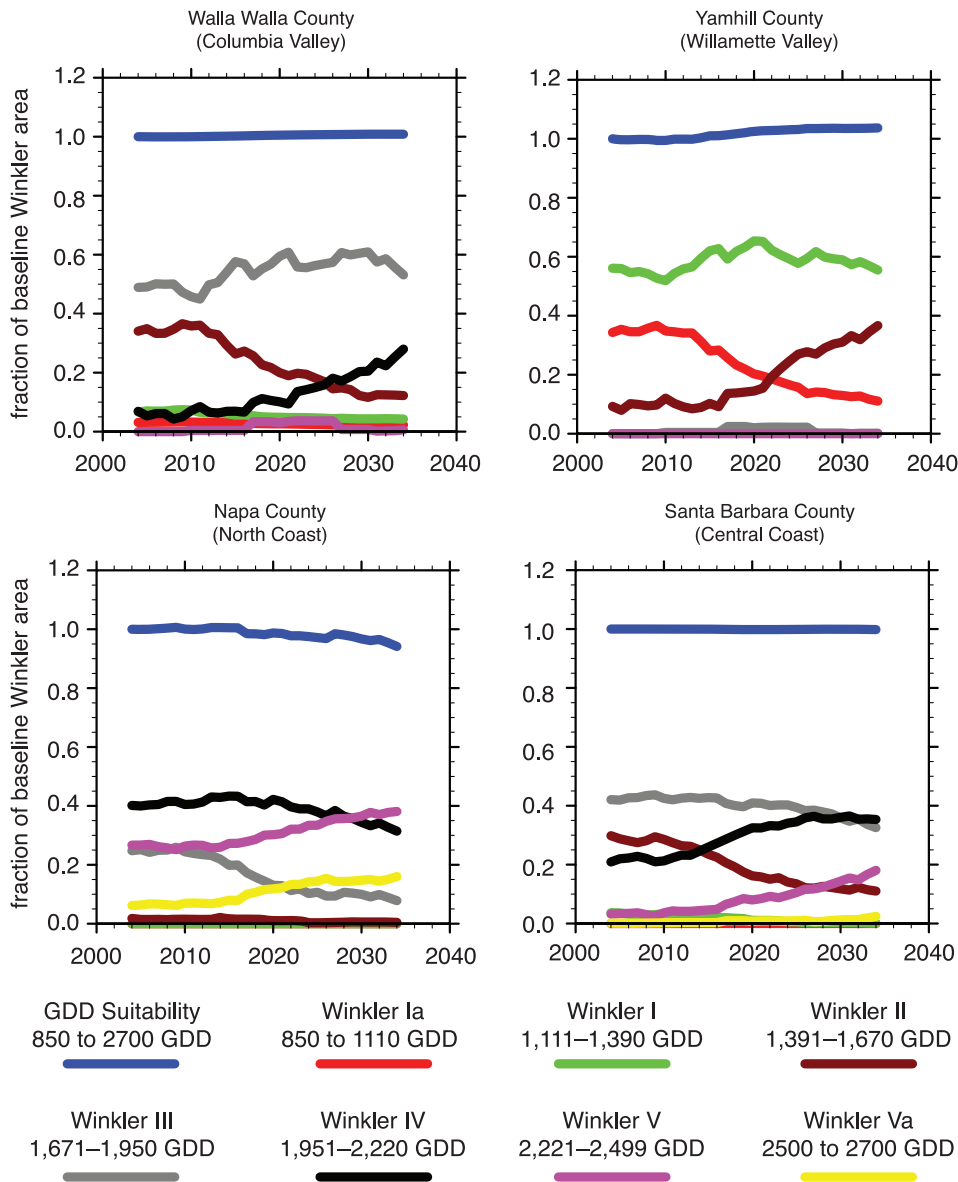
#### 4.2. Climate model uncertainties

The uncertainty in regional climate change is often partitioned into contributions from internal climate system variability, radiative forcing scenario, and climate model formulation (e.g., [52–54]). Although climate models show robust near-term warming over the western US [9, 28, 54], there is some spread across those projections (e.g., [28]). Given that model formulation dominates this spread [52], interpretations of our analysis are limited by the use of a single high-resolution modeling system. However, because fine-scale climate processes can determine the magnitude and spatial variability of high-impact climate change (e.g., [23, 34, 55]), higher resolution is required than is available in the current generation of global climate models. Given the paucity of high-resolution near-term ensemble experiments in the literature [9], further probing of the uncertainty domain will require enhanced investment in such experiments.

Indeed, although our high-resolution model is able to capture the spatial details of temperature in the western US with far more fidelity than the current generation of global climate models [9], the 25 km horizontal resolution is not sufficient to capture all of the microclimatic features that determine temperature suitability, even with bias correction to 1/8-degree resolution. An area of particular concern is the dynamics governing changes in the land–sea breeze and coastal fog, which can ameliorate severely hot temperatures but also lower heat accumulation and increase disease pressure. Twentieth century trends toward increasing strength of coastal winds [56] and cooler coastal temperatures [57] are in agreement with the projection that elevated greenhouse forcing could enhance the land–sea temperature contrast and associated coastal winds [56, 58, 59]. While our high-resolution nested climate model captures those regional-scale atmospheric processes [60], resolving the dynamic response of the land–sea breeze and coastal fog formation will likely require ultra-high-resolution non-hydrostatic modeling systems with coupled high-resolution ocean components, particularly given the complexity of processes influencing coastal sea surface temperatures (e.g., [61–63]).

## 5. Conclusions

We present an initial case study of the climate adaptation wedge framework. This case study is focused on one aspect (temperature suitability) of one climate-sensitive system (premium wine production). However, a number of enhancements could enable greater sophistication and complexity within the wedge framework. For instance,



**Figure 5.** Area in four representative counties that is suitable in each of the Winkler growing degree day (GDD) classes. The Winkler summation is described in table 2, and the representative counties are shown in figure 3. The area is expressed as a fraction of the baseline Winkler area in each county, which is calculated as the total area across all Winkler classes in the 2000–9 period of the five-member ensemble. Each line shows the 10 year running mean of fractional change across the ensemble for a given Winkler class.

process-based impacts models could be used in place of screening criteria. In addition, adaptation wedges could be quantified across a number of domains, as in the case of food systems, which could require wedges associated with heat tolerance (e.g., [10, 64]), irrigation infrastructure [65], trade policy [18], and distribution [66], among others. Further, formal economic analyses could be applied within the wedge framework to quantitatively integrate the costs and benefits of different adaptation actions. Such analyses could include comparisons of local and economy-wide considerations, along with changes in costs and benefits through time and in response to different mitigation and/or adaptation policies.

Our initial treatment illustrates how climate adaptation wedges can enable quantitative analysis of different adaptation targets within the present and future climate. While this

effort represents an initial exploration of one aspect of one industry, with sufficient sophistication the climate adaptation wedge framework could be used to quantitatively evaluate the opportunities and limits of climate adaptation within and across a broad range of natural and human systems.

### Acknowledgments

We thank two anonymous reviewers for insightful and constructive comments. We thank the Rosen Center for Advanced Computing at Purdue for support of computing resources. The analyses presented here were supported by NSF CAREER award 0955283 (Climate and Large-Scale Dynamics, and Geography and Spatial Sciences).

References

- [1] Waxman H A and Markey E J 2009 *American Clean Energy and Security Act of 2009* (Washington, DC: US House of Representatives)
- [2] UNFCCC 2009 *The Copenhagen Accord. Fifteenth session (Copenhagen, Dec. 2009)* vol FCCC/CP/2009/L.7 p 5 (The United Nations)
- [3] Meehl G A *et al* 2005 How much more global warming and sea level rise? *Science* **307** 1769–2
- [4] Wigley T M L 2005 The climate change commitment *Science* **307** 1766–9
- [5] Friedlingstein P and Solomon S 2005 Contributions of past and present human generations to committed warming caused by carbon dioxide *Proc. Natl Acad. Sci. USA* **102** 10832–6
- [6] Solomon S *et al* 2009 Irreversible climate change due to carbon dioxide emissions *Proc. Natl Acad. Sci. USA* **106** 1704–9
- [7] den Elzen M and Meinshausen M 2006 Multi-gas emission pathways for meeting the EU 2 °C climate target *Avoiding Dangerous Climate Change* ed H J Schnellhuber *et al* (Cambridge: Cambridge University Press) pp 299–309
- [8] Meehl G A *et al* 2007 Global climate projections *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon *et al* (Cambridge: Cambridge University Press)
- [9] Diffenbaugh N S and Ashfaq M 2010 Intensification of hot extremes in the United States *Geophys. Res. Lett.* **37** L15701
- [10] Clark R T, Murphy J M and Brown S J 2010 Do global warming targets limit heatwave risk? *Geophys. Res. Lett.* **37** L17703
- [11] Holland M M, Bitz C M and Tremblay B 2006 Future abrupt reductions in the summer Arctic sea ice *Geophys. Res. Lett.* **33** L23503
- [12] Smit B and Wandel J 2006 Adaptation, adaptive capacity and vulnerability *Glob. Environ. Change* **16** 282–92
- [13] Kelly P M and Adger W N 2000 Theory and practice in assessing vulnerability to climate change and facilitating adaptation *Clim. Change* **47** 325–52
- [14] Goklany I 2008 What to do about climate change *Policy Analysis* (Washington, DC: Cato Institute) pp 1–27
- [15] Pielke R Jr *et al* 2007 Lifting the taboo on adaptation *Nature* **445** 597–8
- [16] Aldrich D P and Crook K 2008 Strong civil society as a double-edged sword: siting trailers in post-Katrina New Orleans *Political Res. Quarterly* **61** 379–89
- [17] Adger W N 2003 Social capital, collective action and adaptation to climate change *Econ. Geogr.* **79** 387–404
- [18] Ahmed S A *et al* 2011 Agriculture and trade opportunities for Tanzania: past volatility and future climate change *Rev. Int. Econ.* submitted
- [19] UNFCCC 2007 *Decisions Adopted by the Conf. of the Parties Serving as the Mtg of the Parties to the Kyoto Protocol on Its Third Session, Held in Bali from 3 to 15 December 2007, FCCC/KP/CMP/2007/9/Add.1* (United Nations Framework Convention on Climate Change)
- [20] Brown J, Bird N and Schalatek L 2010 Direct access to the adaptation fund: realising the potential of national implementing entities *Climate Finance Policy Briefs* (Heinrich Boell Foundation and Overseas Development Institute)
- [21] Barr R, Fankhauser S and Hamilton K 2010 Adaptation investments: a resource allocation framework *Mitig. Adapt. Strateg. Clim. Change* **15** 843–58
- [22] Pacala S and Socolow R 2004 Stabilization wedges: solving the climate problem for the next 50 years with current technologies *Science* **305** 968–72
- [23] White M A *et al* 2006 Extreme heat reduces and shifts United States premium wine production in the 21st century *Proc. Natl Acad. Sci.* **103** 11217–22
- [24] White M A, Whalen P and Jones G V 2009 Land and wine *Nat. Geosci.* **2** 82–4
- [25] Jones G V and Goodrich G B 2008 Influence of climate variability on wine regions in the western USA and on wine quality in the Napa Valley *Clim. Res.* **35** 241–54
- [26] Hodgen D A 2008 *US Wine Industry 2008* (Washington, DC: US Department of Commerce) (available at <http://www.trade.gov/td/ocg/wine2008.pdf>)
- [27] Wine Institute 2006 <http://www.wineinstitute.org/resources/pressroom/120720060>
- [28] Christensen J H *et al* 2007 Regional climate projections *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon *et al* (Cambridge: Cambridge University Press)
- [29] Jones G V *et al* 2010 Spatial analysis of climate in winegrape growing regions in the Western United States *Am. J. Enol. Vitic.* **61** 313–26
- [30] Jones G V *et al* 2005 Climate change and global wine quality *Clim. Change* **73** 319–43
- [31] Nemani R R *et al* 2001 Asymmetric warming over coastal California and its impact on the premium wine industry *Clim. Res.* **19** 25–34
- [32] Pal J S *et al* 2007 Regional climate modeling for the developing world: the ICTP RegCM3 and RegCNET *Bull. Am. Meteorol. Soc.* **89** 1395–409
- [33] IPCC, WGI 2000 *Special Report on Emissions Scenarios, Intergovernmental Panel on Climate Change Special Reports on Climate Change* ed N Nakicenovic and R Swart (Cambridge: Cambridge University Press) p 570
- [34] Diffenbaugh N S *et al* 2005 Fine-scale processes regulate the response of extreme events to global climate change *Proc. Natl Acad. Sci. USA* **102** 15774–8
- [35] Collins W D *et al* 2006 The Community Climate System Model version 3 (CCSM3) *J. Clim.* **19** 2122–43
- [36] Meehl G A *et al* 2006 Climate change projections for the twenty-first century and climate change commitment in the CCSM3 *J. Clim.* **19** 2597–616
- [37] Ashfaq M *et al* 2010 Influence of climate model biases and daily-scale temperature and precipitation events on hydrological impacts assessment: a case study of the United States *J. Geophys. Res.* **115** D14116
- [38] Ashfaq M, Skinner C B and Diffenbaugh N S 2010 Influence of SST biases on future climate change projections *Clim. Dyn.* **36** 1303–19
- [39] Daly C *et al* 2000 High-quality spatial climate data sets for the United States and beyond *Trans. ASAE* **43** 1957–62 (PRISM Climate Group, Oregon State University, <http://prism.oregonstate.edu>)
- [40] Frumhoff P C *et al* 2007 *Confronting Climate Change in the US Northeast: Science, Impacts and Solutions. Synthesis Report of the Northeast Climate Impacts Assessment (NECIA)* (Cambridge, MA: Union of Concerned Scientists)
- [41] Hayhoe K *et al* 2004 Emissions pathways, climate change, and impacts on California *Proc. Natl Acad. Sci. USA* **101** 12422–7
- [42] Lobell D B, Cahill K N and Field C B 2007 Historical effects of temperature and precipitation on California crop yields *Clim. Change* **81** 187–203
- [43] Winkler A *et al* 1974 *General Viticulture* 4th edn (Berkeley, CA: University of California Press) p 740
- [44] Amerine M A and Winkler A J 1944 Composition and quality of musts and wines of California grapes *Hilgardia* **15** 493–675
- [45] Jones G V 2007 Climate change and the global wine industry *Proc. 13th Technical Conf. Australian Wine Industry (Adelaide)*

- [46] Bisson L F *et al* 2002 The present and future of the international wine industry *Nature* **418** 696–9
- [47] Schultz H R 2010 Climate change and viticulture: research needs for facing the future *J. Wine Res.* **21** 113–6
- [48] Gergaud O and Livat F 2007 How do consumers use price to assess quality? *AAWE Working Paper 13* (American Association of Wine Economists)
- [49] Delmas M A and Grant L E 2008 Eco-labeling strategies: the eco-premium puzzle in the wine industry *AAWE Working Paper 13* (American Association of Wine Economists)
- [50] Szolnoki G, Herrmann R and Hoffmann D 2010 Origin, grape variety or packaging? Analyzing the buying decision for wine with a conjoint experiment *AAWE Working Paper 72* (American Association of Wine Economists)
- [51] Pecotich A and Ward S 2010 Taste testing of wine by expert and novice consumers in the presence of variations in quality, brand and country of origin cues *AAWE Working Paper 66* (American Association of Wine Economists)
- [52] Hawkins E and Sutton R 2009 The potential to narrow uncertainty in regional climate predictions *Bull. Am. Meteorol. Soc.* **90** 1095–107
- [53] Deque M *et al* 2005 Global high resolution versus Limited Area Model climate change projections over Europe: quantifying confidence level from PRUDENCE results *Clim. Dyn.* **25** 653–70
- [54] Hawkins E and Sutton R 2010 The potential to narrow uncertainty in projections of regional precipitation change *Clim. Dyn.* at press ([doi:10.1007/s00382-010-0810-6](https://doi.org/10.1007/s00382-010-0810-6))
- [55] Rauscher S A *et al* 2008 Future changes in snowmelt-driven runoff timing over the western US *Geophys. Res. Lett.* **35** L16703
- [56] Bakun A 1990 Global climate change and intensification of coastal ocean upwelling *Science* **247** 198–201
- [57] Lebassi B *et al* 2009 Observed 1970–2005 cooling of summer daytime temperatures in coastal California *J. Clim.* **22** 3558–73
- [58] Snyder M A *et al* 2003 Future climate change and upwelling in the California current *Geophys. Res. Lett.* **30** 1823
- [59] Diffenbaugh N S, Snyder M A and Sloan L C 2004 Could CO<sub>2</sub>-induced land cover feedbacks alter near-shore upwelling regimes? *Proc. Natl Acad. Sci.* **101** 27–32
- [60] Diffenbaugh N S and Ashfaq M 2007 Response of California current forcing to mid-Holocene insolation and sea surface temperature *Paleoceanography* **22** PA3101
- [61] Marchesiello P, McWilliams J C and Shchepetkin A 2003 Equilibrium structure and dynamics of the California current System *J. Phys. Oceanogr.* **33** 753–83
- [62] Mendelsohn R and Schwing F B 2002 Common and uncommon trends in SST and wind stress in the California and Peru–Chile current systems *Prog. Oceanogr.* **53** 141–62
- [63] Large W G and Danabasoglu G 2006 Attribution and impacts of upper ocean biases in CCSM3 *J. Clim.* **19** 2325–46
- [64] Battisti D S and Naylor R L 2009 Historical warnings of future food insecurity with unprecedented seasonal heat *Science* **323** 240–4
- [65] Doll P 2002 Impact of climate change and variability on irrigation requirements: a global perspective *Clim. Change* **54** 269–93
- [66] Gregory P J, Ingram J S I and Brklacich M 2005 Climate change and food security *Phil. Trans. R. Soc. B* **360** 2139–48
- [67] Jones G V 2005 Climate change in the western United States grape growing regions *Acta Horticulturae* (ISHS) **689** 41–60