Extreme heat reduces and shifts United States premium wine production in the 21st century

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Premium wine production is limited to regions climatically conducive to growing grapes with balanced composition and varietal typicity. Three central climatic conditions are required: (*i*) adequate heat accumulation; (*ii*) low risk of severe frost damage; and (*iii*) the absence of extreme heat. Although wine production is possible in an extensive climatic range, the highest-quality wines require a delicate balance among these three conditions. Although historical and projected average temperature changes are known to influence global wine quality, the potential future response of wine-producing regions to spatially heterogeneous changes in extreme events is largely unknown. Here, by using a high-resolution regional climate model forced by the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios A2 greenhouse gas emission scenario, we estimate that potential premium winegrape production area in the conterminous United States could decline by up to 81% by the late 21st century. While increases in heat accumulation will shift wine production to warmer climate varieties and/or lower-quality wines, and frost constraints will be reduced, increases in the frequency of extreme hot days (>35°C) in the growing season are projected to eliminate winegrape production in many areas of the United States. Furthermore, grape and wine production will likely be restricted to a narrow West Coast region and the Northwest and Northeast, areas currently facing challenges related to excess moisture. Our results not only imply large changes for the premium wine industry, but also highlight the importance of incorporating fine-scale processes and extreme events in climate-change impact studies.

climate change | enology | grape | viticulture | winegrape

A number of observations indicate that warming has occurred during the late 20th and early 21st centuries at the Earth's surface (1), in the troposphere (2–4), and in the oceans (5). The majority of this warming has likely been caused by anthropogenic greenhouse gas (GHG) emissions (6), and if such emissions continue unabated, global mean temperatures are likely to rise by 2–6°C over the next century (1). This mean global warming will likely manifest itself over a range of spatial and temporal scales, altering mean seasonal climate (e.g., ref. 7), interannual climate variability (e.g., ref. 8), and the frequency and magnitude of extreme events (e.g., refs. 9–11).

Such climatic changes could have a wide variety of important impacts on sectors such as human health (12), biological invasions (13), species extinctions (14), and water (15) and energy (16) resources. Because the quality and production of cultivated crops are directly influenced by local climate variables, agricultural systems may be particularly susceptible to climate change. For at least five reasons, the cultivation of grapes for the production of premium wine provides an optimal case for assessing potential impacts of climate change. First, premium wines are produced conterminously with human habitation and recording of climate and weather variables. Second, premium wines are intensively studied, both analytically and aesthetically, yielding long time series of response variables (17). Third, although technological innovations are an important influence on wine quality, premium wine is fundamentally limited by the availability of high-quality winegrapes. Fourth, high-quality winegrapes are produced almost exclusively in a narrow climatic range characterized by a lack of both extreme heat and extreme cold. Fifth, premium wine production is of intense economic and cultural importance in the United States, which ranks as the fourth largest grape producer in the world with ≈6 million tons harvested (3.5 million tons for winegrapes alone) at an economic value of $2.9 billion annually (18). California alone accounts for >90% of U.S. production with 2.7 million tons of winegrapes produced on >500,000 acres (19). In California, the wine industry has an overall economic impact of >$45 billion annually (Wine Institute of California, www.wineinstitute.org).

Based on these premises, we investigate the response of the distribution of premium winegrape-producing regions in the United States to potential climate changes induced by increased GHG forcing. Although recent work has tested the response of these regions to potential mean changes in large-scale climate processes (17), it is now well established that fine-scale climate processes can regulate the response of regional climate, and in particular extreme climate, to enhanced GHG forcing (e.g., refs. 9 and 20–22). Our goal here is therefore to model the distribution of premium winegrape-producing regions at present and for simulated future climates across the conterminous United States, with specific emphasis on the effects of changes in the frequency and magnitude of extreme events on winegrape quality and production.

To date, studies assessing potential agricultural responses to 21st-century climate conditions (23) have lacked sufficient spatial resolution and/or spatial extent to resolve the range of climate processes likely to influence subregional-scale climate–agriculture relationships across large continental areas. The recent availability of a high-resolution (25 km) future climate simulation for the full conterminous United States (9) thereby offers a unique opportunity for continental-scale assessment of the potential impacts of future climate change on agricultural systems. We apply this high-resolution climate projection to the problem of premium winegrape production in the United States, first evaluating modern climate–winegrape relationships with a multivariate temperature approach at 1-km resolution, and then projecting the distribution of premium winegrape production in the late 21st century by using the high-resolution climate model simulations. Because they integrate projected changes in fine spatial- and temporal-scale climatic controls over a large spatial

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Abbreviations: GHG, greenhouse gas; HTCT, heat tolerant and cold tolerant; HICT, heat intolerant and cold tolerant; HTCI, heat tolerant and cold intolerant; HICI, heat intolerant and cold intolerant; RF, reference integration; RegCM3, Abdus Salam Institute for Theoretical Physics regional climate model.

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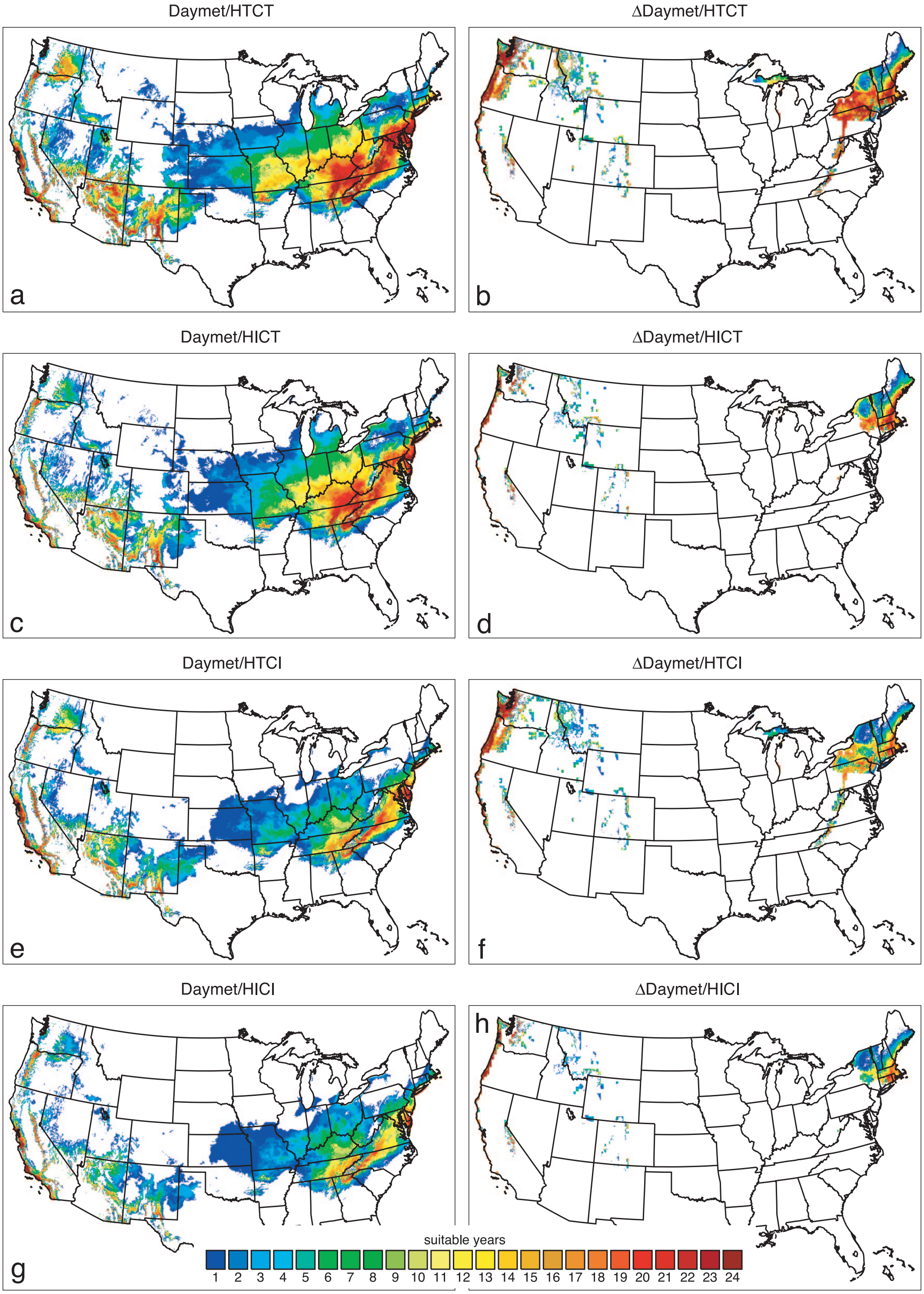

Fig. 1. Suitable years (of 24 possible) for premium winegrape production in the current (Daymet) and future (ΔDaymet) climates for four categories of grape/vine tolerance to extreme temperatures: HTCT (*a* and *b*), HICT (*c* and *d*), HTCI (*e* and *f*), and HICI (*g* and *h*).

extent, our results are not only relevant to an important agricultural industry, but are also illustrative of the potential impact of spatially heterogeneous changes in extreme event frequency and magnitude on natural and human systems.

Results

Our simulations suggest that the area available for production of premium winegrapes will both contract and shift over the next century (Fig. 1). In the baseline Daymet climate (see *Methods*), premium winegrape production was consistently possible throughout much of the western United States, particularly the West Coast, the western slope of the Sierra Nevada Mountains, extensive regions of the Southwest, and much of the mideastern seaboard (Fig. 1 *a*, *c*, *e*, and *g*). Marginally favorable regions existed in many areas of the central United States. Selection of the thermal tolerance category [heat tolerant and cold tolerant

Table 1. Identification of potential premium winegrape-producing area for four heat/cold tolerance categories

Criterion	HTCT	HICT	HTCI	HICI
GS growing-degree days	1111–2499	1111–2499	1111–2499	1111–2499
GS average temperature	13–20°C	13–20°C	13–20°C	13–20°C
GS and RS hot days	14	7	14	7
W and S/F cold days	14	14	7	7
GS and RS diurnal temperature range	20°C	20°C	20°C	20°C

Pixels must have less than the specified number of hot/cold days (see text for details) and diurnal temperature range. Seasons: growing season (GS), April 1 to October 31; ripening season (RS), August 15 to October 15; winter (W), December 1 to February 28; spring (S), March 1 to May 31; fall (F), September 1 to November 30.

(HTCT), heat intolerant and cold tolerant (HICT), heat tolerant and cold intolerant (HTCI), heat intolerant and cold intolerant (HICI); see *Methods*] changed the number of suitable years and the distribution limits but not the overall features of the distribution. In the projected future ΔDaymet climate (see *Methods*), premium winegrape-producing regions were eliminated from most of the Daymet climate distribution. Production potential was almost completely eliminated in the Southwest and central United States; only high elevations were marginally suitable in the intermountain West. Consistently favorable regions remained along coastal California but new and high-quality regions were created in coastal Oregon and Washington. In HTCT, much of the Northeast was consistently favorable with other levels of tolerance reducing potential distribution.

The reduction in area between the Daymet and ΔDaymet climates was 81% when including marginal pixels (those with at least one valid climate year in the multivariate analysis; see *Methods* and Table 1), followed by 60% in the mean climate multivariate analysis and 14% in the Winkler analysis (Fig. 2). The shift to the ΔDaymet climate was also associated with variable shifts in the percent of pixels in the highest-quality Winkler regions I and II (see *Methods*). Considering only the Winkler analysis, i.e., no assessment of extreme temperatures, region I or II was 52% of the Daymet winegrape distribution and 28% of the ΔDaymet climate. Conversely, the percent of regions I and II in ΔDaymet actually increased when using either the multivariate marginal (36–60%) or multivariate mean climate (40–47%) accounting criteria (Fig. 2).

The reduction and shift in extent was the result of three central changes in climate metrics (Fig. 3). First, the average thermal condition, as represented by changes in growing-degree days (Fig. 3*a*) and growing-season average temperature (Fig. 3*b*), allowed potential winegrape-producing areas to move northward and toward higher elevations. Second, growing season (Fig. 3*c*) and ripening-season (Fig. 3*d*) hot days (detrimental to winegrape production; see *Methods*) increased by 3–8 weeks in much of the south-central and southwestern United States, thereby eliminating premium winegrape production from these regions. Third, especially in the Northeast winter (Fig. 3*e*) and Rocky Mountain spring/fall (Fig. 3*f*), cold days often declined by >3 weeks: in many of the coldest regions of the United States, the extreme cold limitation was reduced or eliminated.

From the baseline Winkler distribution of 3.54 million km^2 (identical to the ΔDaymet Winkler bar in Fig. 2), growing season hot days alone reduced winegrape production area by 2.84 million km^2 (Fig. 4). Cold days in winter and spring/fall were also important, reducing winegrape production area by ≈1.5 million km^2, indicating that even in a warmed climate, extreme cold still limits winegrape production. Changes in growing season average temperature, ripening-season hot days, and diurnal temperature range were less important.

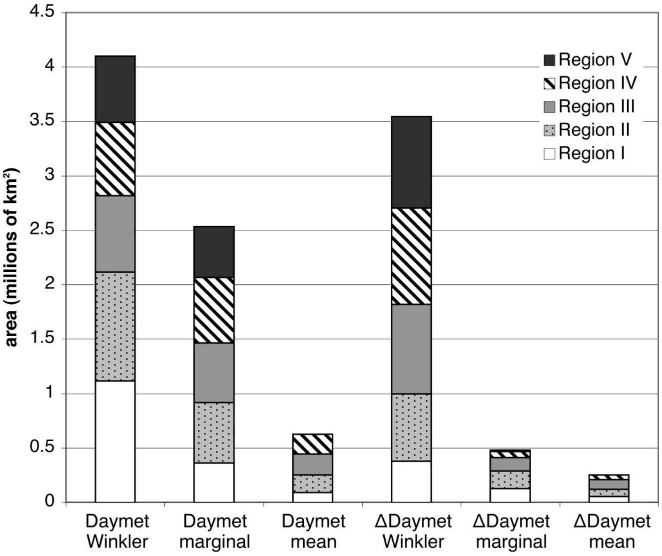

Fig. 2. Winegrape-producing area in the Daymet and ΔDaymet climates. For each climate, the three analyses are: (*i*) Winkler, the area defined by the presence of valid Winkler regions in the 24-year mean climate; (*ii*) marginal, showing area in the multivariate analysis with at least 1 year suitable for winegrape production; and (*iii*) mean, showing area in the multivariate analysis with the 24-year mean climate suitable for winegrape production.

Based on the central importance of growing season hot days we recalculated the timing of the growing season in the ΔDaymet climate. We first calculated the average growing-degree day summation in the Daymet record from January 1 to April 1 and then calculated the average date for each pixel in the ΔDaymet climate at which this summation was reached. On average, the growing season began 22 days earlier in ΔDaymet with the largest changes along the West Coast. Based on the earlier initiation of the growing season but by using the same duration of 214 days, we recalculated, as described in *Methods*, ΔDaymet growing season hot days. Furthermore, as the timing shifted toward earlier growth, we also recalculated the ripening-season hot days. We then calculated the difference in total area for the mean climate multivariate analysis. Differences were minor: area increased by 4,700 km^2 when considering shifts in the growing and ripening seasons and by 4,100 km^2 when considering shifts in the growing season alone.

Discussion

Geographical shifts in historical and projected viticultural regions, as we have shown here, are not unusual. Vineyards planted during the "Little Optimum" in southern England and along the North and Baltic Seas (24) subsequently failed during the Little Ice Age. Burgundy spring–summer temperatures as warm as the 1990s have occurred several times in the region since 1370 (25). In the principal winegrape-growing regions of California, Oregon, and Washington, growing season temperatures have warmed by 0.9°C from 1948 to 2002, driven mostly by changes in minimum temperatures (26). In future climates, likely changes include: varietal suitability shifts in many regions (17); increased heat stress and irrigation pressure but decreased frost risk in Australia (27); northward migration of European wine-producing regions (28); and shifts in Australian wine production to southern and coastal areas (29).

However, our simulations suggest that consideration of mean climate alone may dramatically underestimate climate change impacts. Independent of both the category used to characterize

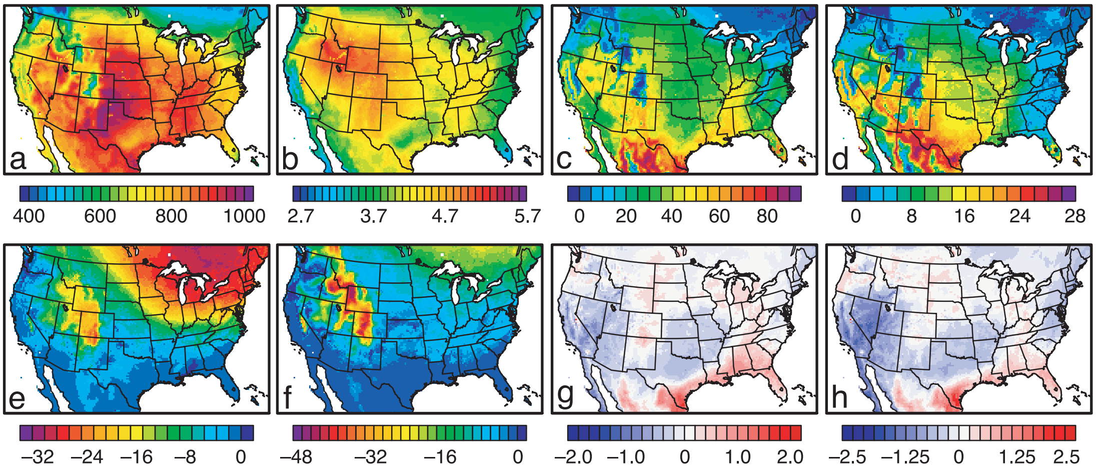

Fig. 3. Projected changes in climate variables (A2—RF). (*a*) Growing season growing-degree days. (*b*) Growing season average temperature (°C). (*c*) Growing season hot days (days per year). (*d*) Ripening-season hot days (days per year). (*e*) Winter cold days (days per year). (*f*) Spring and fall cold days (days per year). (*g*) Growing season diurnal temperature range (°C). (*h*) Ripening season diurnal temperature range (°C).

grape/vine tolerance to extreme temperature (Fig. 1) and the criteria used to assess climate metrics (Fig. 2), the area available for winegrape production is likely to decline in the 21st century ΔDaymet climate. In our analyses, the largest reductions were caused mainly by projected increases in the frequency of extreme hot days during the growing season (Figs. 3 and 4), the primary cause of which was the enhanced radiative forcing associated with higher GHG concentrations [A2 integration CO_2 concentrations are intermediate between the endpoints assessed by Hayhoe *et al.* (30)]. Additionally, climate system feedbacks enhanced this heating effect, as in the Southwest where increases in extreme hot events were associated with decreased summer soil moisture and enhanced anticyclonic flow aloft (9). Climate system feedbacks also contributed to areal expansion of potential winegrape production in the Mountain West where fine-scale albedo feedbacks associated with loss of snow cover enhanced the warming effects of elevated GHG concentrations.

The total predicted change in area available for winegrape production exhibits several important nuances. First, when assessed with Winkler regions alone, i.e., ignoring the effects of extreme temperatures, the winegrape-producing area declined only slightly (Fig. 2). This projection may be considered to represent regional abilities to produce generic, not premium, wines. The strong reduction in regions I and II indicates that the overall shift would be toward higher yields of lower-quality fruit, resulting in lower-quality and lower-priced wines. Second, when including the effects of extreme temperatures but including marginal production areas, the central effect of the ΔDaymet climate is to eliminate many of the marginal pixels in the Daymet climate (blue and green areas in Fig. 1), creating, in essence, high-quality refugia. Third, when considering the effects of extreme temperature but using the 24-year mean climate metrics (most representative of a consistent potential for premium winegrape production), the area in regions I and II declined from 0.25 million km^2 in the Daymet climate to 0.12 million km^2 in ΔDaymet (Fig. 2), implying that the area capable of producing the highest-quality, most expensive wines is likely to be reduced by >50%. Fourth, shifting the timing of the growing and ripening seasons had little effect on predicted ΔDaymet distributions, suggesting that the overall increase in extreme heat (Fig. 3 *c* and *d*) overwhelms more subtle shifts in the timing of growingseason onset.

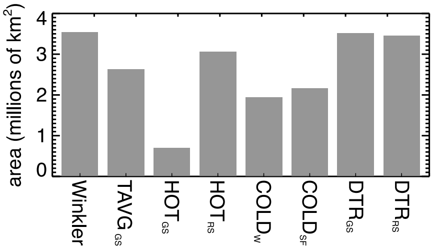

Fig. 4. Single factor reductions in winegrape-producing area for the heat-tolerant and cold-tolerant category. From left to right, factors are: Winkler regions; growing season average temperature (TAVG$_{GS}$); hot days in growing (HOT$_{GS}$) and ripening (HOT$_{RS}$) seasons; cold days in winter (COLD$_{W}$) and spring/fall (COLD$_{SF}$); and diurnal temperature range in growing (DTR$_{GS}$) and ripening (DTR$_{RS}$) seasons.

Further, projected climate changes shift premium winegrape production to high humidity/precipitation regions of the Pacific Northwest and New England. High humidity is associated with higher risk of quality-reducing factors such as various forms of rot (31) and powdery mildew (32), and higher frequency of raindrop impacts on leaves increases fungal dispersal (33). The refugial premium winegrape production areas, which are projected to experience increased atmospheric water vapor mixing ratio in the A2 climate (9), are therefore likely to require extensive pathology control measures and/or will experience declines in winegrape quality.

The projected decrease in potential winegrape-producing area is based on current vine stock characteristics and does not consider advances in viticultural technology or management, both of which may extend winegrape production in the current distribution. For example, grapevine breeding programs, which have historically focused on disease and cold resistance (34), will likely act to increase the development of heat-resistant vine stock. Specific viticultural techniques may also increase resistance to extreme heat (e.g., ref. 35). DeBolt *et al.* (36) have identified the key gene for the enzymatic conversion of vitamin C to tartaric acid, the compound most influencing perceptions of wine quality, suggesting that, given continued genetic (37), breeding, and vineyard adaptation, the wine industry may be able to moderate the effects of increased extreme heat.

Conclusions

Changes in the frequency of extreme temperatures may have a more extreme effect on biological and agricultural systems than changes in mean climate. Here, using historical climate records and a regional climate model capable of resolving fine-scale climate processes, we found that changes in mean climate between the late 20th century and the late 21st century caused only minor reductions in the total area available for winegrape production. However, when we included the effects of extreme temperatures, principally extreme heat in the growing season, areas marginally suitable for winegrape production in the current climate were nearly eliminated and the area capable of consistently producing grapes required for the highest-quality and highest-priced wines declined by >50%. These changes would have substantial effects on the wine industry in the United States. Based on these results, we strongly suggest that climate change impact studies continue to increase the use of high-resolution climate simulations capable of resolving changes in extreme climate events.

Methods

Current Potential Distribution. We used the Daymet dataset (ref. 38; www.daymet.org) 1980–2003 1-km gridded daily records of maximum and minimum temperature to assess potential premium winegrape-producing areas in the late 20th and early 21st century. We developed a winegrape production suitability screening system, as described below, in which we annually assessed whether or not each pixel was climatically suitable for premium winegrape production. The process thus yielded the number of years (of 24) in which premium winegrapes could be grown. Note that our process identifies thermally regulated potential winegrape production and does not consider moisture factors or the complete framework of "*terroir*": the integral climate, soil, varietal, and cultural factors influencing local winegrape quality.

Although wines are produced in all 48 states of the conterminous United States, the cultivation of premium grapes for wine production is limited to specific regions. The exact delimitation of these regions in the late 20th and early 21st century is, however, subjective. A definition based on the climate characteristics of the Napa and Sonoma Valleys, for example, will preclude the identification of the Willamette Valley in western Oregon, in which high-quality pinot noir is produced. Assignment of thresholds for extreme temperature tolerance is similarly subjective. For example, although several days of temperatures exceeding 30°C can benefit ripening potential, prolonged periods can induce heat stress in the plant and lead to premature véraison, the elimination of the berries through abscission, permanent enzyme inactivation, and partial or total failure of flavor ripening (39); the transition point is varietally dependent. Injury and/or death as a direct or indirect result of the formation of ice within tissues and the resulting stresses to the vine can dramatically affect yield and/or quality but cold hardiness is seasonally and genetically variable and is subject to cultural practices (e.g., timing of pruning) (39). Based on these uncertainties, especially in winegrape tolerance to extreme temperature events, we developed a three-step screening process based on generalized *a priori* estimates of temperature thresholds and tolerances: (*i*) define the general thermal regime requirements; (*ii*) establish the criteria defining an extreme temperature event; and (*iii*) produce a range of categories of winegrape tolerance to extreme temperature events.

We based the general thermal regime requirement on three criteria. First, we calculated the growing season (see Table 1 for calendar definitions of all seasons) base 10°C growing-degree day summation and established the Winkler region (40, 41). Regions I (1,111–1,390 growing-degree days) and II (1,391–1,670 growing-degree days) generally produce the best dry table wines with light to medium body and good balance. Region III (1,671–1,950 growing-degree days) produces full-bodied dry and sweet wines. Region IV (1,951–2,220 growing-degree days) is best for fortified wines, with table wines being inferior. Region V (2,220–2,499 growing-degree days) is best for table grapes and makes low-quality table wines. We rejected all pixels outside the full 1,111–2,499 growing-degree day Winkler region range. Second, based on a global survey of premium wine ratings (17), we eliminated all pixels with growing season average temperature <13°C or >20°C. Third, equitable (low) diurnal temperature ranges are associated with optimal ripening conditions for high-quality wines (42); therefore we eliminated pixels with diurnal temperature ranges >20°C during either the growing or ripening seasons.

Based on literature estimates, we assigned temperature thresholds to represent daily extreme temperature events. Growing season and ripening-season hot days, defined as days with maximum temperature >35°C, are related to the generalized upper limit for grapevine photosynthesis (42), lowest grapevine dry matter production,[‖] and inhibition of color development (43). Cold days, defined as days with minimum temperature below −12.2°C in winter and −6.7°C in spring/fall, are related to bud and wood loss (44) and grapevine fatality (40, 41).

Finally, we generated four categories designed to represent the geographic uncertainty in varietal tolerance: HTCT, HICT, HTCI, and HICI. Within each category, we defined low tolerance levels as 7 days and high tolerance levels as 14 days (see Table 1 for details).

Future Potential Distribution. For this study, we extended the 25-km-resolution climate simulations reported by Diffenbaugh *et al.* (9). Two 29-year simulations were completed for the conterminous United States by using the Abdus Salam Institute for Theoretical Physics regional climate model (RegCM3) (45–47): one reference integration (RF) for the late 20th-century climate conditions (1961–1989) and one (A2) for future climate conditions (2071–2099) under the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios A2 GHG emission scenario (48). RegCM3 was forced at the lateral boundaries by fields from global time-slice simulations carried out with the National Aeronautics and Space Administration finite volume element model [see Coppola and Giorgi (49) for a detailed description of the global climate model experiments]. The first year of each integration was run twice to allow the RegCM3 to equilibrate, and the initial iteration was discarded from the analysis.

To correct systematic model biases and capture the spatial heterogeneity reflected in the observational climate data, we have used an anomaly (or Δ) technique to create the future climate inputs for the winegrape production calculations. For the RegCM3 RF and A2 climate model simulations, we first calculated the climate metrics of growing season degree day summations, growing season average temperatures, number of hot days in the growing and ripening seasons, number of cold days in spring/fall and winter, and growing and ripening season diurnal temperature ranges. We then calculated RegCM3-simulated differences (A2 minus RF) in the climate metrics, reprojected those data from the RegCM3 25-km grid to the Daymet 1-km grid (ENVI 4.0), and added the difference values to the Daymet climate metrics, thus creating a ΔDaymet data set of 1-km climate metrics. We then calculated, for each pixel, 24 annual ΔDaymet values to determine whether or not pixels were valid winegrape-producing regions.

Analysis. We conducted a five-step analysis. First, for HTCT, HICT, HTCI, and HICI categories in both the Daymet and ΔDaymet climates, we visualized the winegrape production suitability of each pixel as a 0- to 24-year scale, with 0 being no potential for winegrape production and 24 being production suitability in every year. Second, we calculated the total area in

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[‖] Buttrose, M. (1974) *CAB Horticultural Abstracts* **44,** 319–326.

Winkler regions I–V in the Daymet and ΔDaymet climates based on three criteria: (*i*) 24-year mean growing season growing-degree summations to calculate Winkler regions alone, i.e., no consideration of extreme temperatures; (*ii*) multivariate screening factors, but including pixels with at least one valid winegrape production year, i.e., including marginal production regions; and (*iii*) multivariate screening factors but using a 24-year mean climatology, not individual years. For criteria *ii* and *iii* we used the average distribution from the HTCT, HICT, HTCI, and HICI categories. Third, to understand the underlying climatic conditions leading to changes in winegrape production distribution, we calculated and visualized the A2 minus RF differences in the climate metrics. Fourth, to isolate the effects of changes in specific metrics, we re-executed the winegrape suitability assessment by using the eight separate screening factors, the mean climate metrics (most representative of long-term winegrape production suitability), and the HTCT screening levels (results similar for HICT, HTCI, and HICI categories not presented). Finally, based on results from step four and as described, we tested the impact of shifts in the timing of the seasons (50) containing the most critical temperature metric.

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