Climate change, wine, and conservation

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Climate change is expected to impact ecosystems directly, such as through shifting climatic controls on species ranges, and indirectly, for example through changes in human land use that may result in habitat loss. Shifting patterns of agricultural production in response to climate change have received little attention as a potential impact pathway for ecosystems. Wine grape production provides a good test case for measuring indirect impacts mediated by changes in agriculture, because viticulture is sensitive to climate and is concentrated in Mediterranean climate regions that are global biodiversity hotspots. Here we demonstrate that, on a global scale, the impacts of climate change on viticultural suitability are substantial, leading to possible conservation conflicts in land use and freshwater ecosystems. Area suitable for viticulture decreases 25% to 73% in major wine producing regions by 2050 in the higher RCP 8.5 concentration pathway and 19% to 62% in the lower RCP 4.5. Climate change may cause establishment of vineyards at higher elevations that will increase impacts on upland ecosystems and may lead to conversion of natural vegetation as production shifts to higher latitudes in areas such as western North America. Attempts to maintain wine grape productivity and quality in the face of warming may be associated with increased water use for irrigation and to cool grapes through misting or sprinkling, creating potential for freshwater conservation impacts. Agricultural adaptation and conservation efforts are needed that anticipate these multiple possible indirect effects.

vinecology | wildlife | ecosystem services

Viticulture is famously sensitive to climate (1–8) and changes in wine production have been used as a proxy to elucidate past climate change (9). Temperature and moisture regimes are among the primary elements of *terroir* (10, 11), with growing season temperature being particularly important in delimiting regions suitable for growing wine grapes (*Vitis vinifera*). Mediterranean climate regions (warm and dry summers; cool and wet winters) are particularly suitable for viticulture (4), while at the same time having high levels of biodiversity, endemism, and habitat loss, making them global biodiversity hotspots (12–14). Climate change has the potential to drive changes in viticulture that will impact Mediterranean ecosystems and to threaten native habitats in areas of expanding suitability (15). These impacts are of broad significance because they may be illustrative of conservation implications of shifts in other agricultural crops.

Vineyards have long-lasting effects on habitat quality and may significantly impact freshwater resources. Vineyard establishment involves removal of native vegetation, typically followed by deep plowing, fumigation with methyl bromide or other soil-sterilizing chemicals, and the application of fertilizers and fungicides (16, 17). Mature, producing vineyards have low habitat value for native vertebrates and invertebrates, and are visited more often by nonnative species (18, 19). Thus, where vineyards are established, how they are managed, and the extent to which they replace native habitats have large implications for conservation (20, 21).

Water use by vineyards creates conservation concern for freshwater habitats (22, 23). Vineyard water use for frost damage prevention has resulted in significant flow reduction in California streams (23). In a warming climate, water use may increase as vineyard managers attempt to cool grapes on the vine to reduce quality loss from heat stress and to reduce drought stress (23). Potential damage to freshwater environments is generally highest where water is already scarce (24). Climate change may bring precipitation decreases to some regions, increasing the need for irrigation, which may result in impacts on freshwater ecosystems. Traditions of vineyard irrigation, limited in Europe (25) and higher in other parts of the world (e.g., California, Chile) (26), may moderate or accentuate these water use issues. Overall, vineyard establishment and management have significant implications for terrestrial and freshwater conservation, which may be significantly impacted by climate change.

Here we model potential global changes in climatic suitability for viticulture resulting from climate change to assess possible attendant impacts on terrestrial and freshwater ecosystem conservation. We use the consensus of multiple wine grape suitability models representing a range of modeling approaches driven by 17 global climate models (GCMs) under two Representative Concentration Pathways (RCPs). Habitat impact is assessed by using an "ecological footprint" index, which measures the intersection of viticultural suitability with remaining natural habitat (27). The potential for impact on freshwater provisioning is assessed by using the intersection of water stress (28), projected changes in suitability for viticulture and projected changes in rainfall.

Results

Major global geographic shifts in suitability for viticulture are projected by the consensus of our wine grape suitability models (Fig. 1 and Fig. S1), between current (mean of 1961–2000) and 2050 (mean of 2041–2060), with high agreement among the results obtained with the 17 GCMs. Suitability is projected to decline (Fig. 1, red) in many traditional wine-producing regions (e.g., the Bordeaux and Rhône valley regions in France and Tuscany in Italy) and increase in more northern regions in North America and Europe, under RCP 8.5 and RCP 4.5. Current suitability is projected to be retained [50% of GCMs (Fig. 1, light green) and 90% of GCMs (Fig. 1, dark green)] in smaller areas of current wine-producing regions, especially at upper elevations and in coastal areas. At higher latitudes (Fig. 1, main map) and elevations (Fig. 1, *Insets*), areas not currently suitable for viticulture are projected to become suitable in the future [50% of GCMs (Fig. 1, light blue) and 90% of GCMs (Fig. 1, dark blue)].

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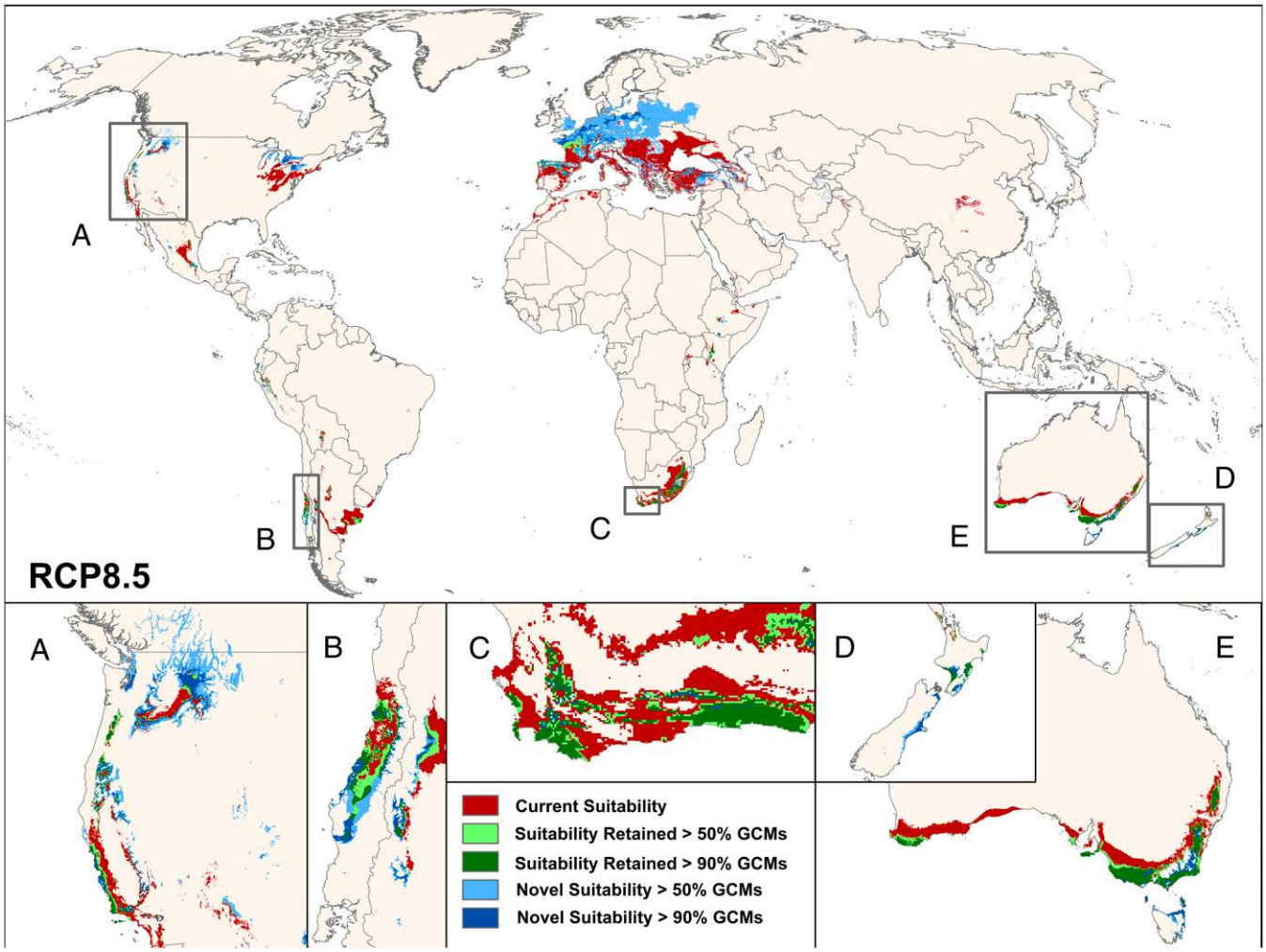

Fig. 1. Global change in viticulture suitability RCP 8.5. Change in viticulture suitability is shown between current (1961–2000) and 2050 (2041–2060) time periods, showing agreement among a 17-GCM ensemble. Areas with current suitability that decreases by midcentury are indicated in red (>50% GCM agreement). Areas with current suitability that is retained are indicated in light green (>50% GCM agreement) and dark green (>90% GCM agreement), whereas areas not suitable in the current time period but suitable in the future are shown in light blue (>50% GCM agreement) and dark blue (>90% GCM agreement). *Insets*: Greater detail for major wine-growing regions: California/western North America (*A*), Chile (*B*), Cape of South Africa (*C*), New Zealand (*D*), and Australia (*E*).

To understand these geographic shifts in more detail, we examine ensemble mean change and variation among the 17 GCMs for nine major wine-producing regions (Fig. 2). Five of these regions have Mediterranean climate, two (non-Mediterranean Australia and New Zealand) are important non-Mediterranean wine-producing regions, and two are areas in which viticultural suitability is projected to expand greatly in the future. In the Mediterranean-climate wine-producing regions, mean suitability decrease ranges from 25% in Chile to 73% in Mediterranean Australia under RCP 8.5 and from 19% to 62% under RCP 4.5 (Fig. 2). Non-Mediterranean Australia sees slight decreases in suitable area whereas large increases in suitable area are projected for New Zealand. Large newly suitable areas are projected in regions of Northern Europe and western North America. Ensemble mean increases in suitable area are 231% in western North America and 99% in Northern Europe in RCP 8.5, and 189% and 84% under RCP 4.5 (Fig. 2). Model agreement is high, with all but two models indicating declining suitability in Mediterranean climate regions and all models projecting increasing suitability in New Zealand, western North America, and Northern Europe (Fig. 2). These changes in suitability for viticulture may have impacts on terrestrial and freshwater systems of conservation importance.

The intersection of viticultural suitability and natural habitats defines the potential ecological footprint of viticulture (Table 1). Potential ecological footprint is projected to increase most strongly in Mediterranean Europe (+342% under RCP 8.5), where suitability expands upslope into remaining montane areas containing some of Europe's most natural lands. Elevation shifts in suitability drive substantial footprint increases in the Cape of South Africa (mean increase of 14% under RCP 8.5) and California (mean increase of 10% under RCP 8.5). In contrast, Chile and Australia see future suitability increases in valleys and coastal areas that are heavily populated (with little remaining natural habitat), so there is little change in mean ecological footprint and significant model disagreement in sign of change.

Large increases in ecological footprint are projected in New Zealand, western North America, and Northern Europe. The highest percent change in footprint is in Northern Europe (191% under RCP 8.5), followed by New Zealand (126% under RCP 8.5). Western North America has the highest absolute area increase, as its change (16%) is on a very high existing footprint value (44%) over a large area (4.9 million ha). Model agreement is high for New Zealand and western North America, but lower for Northern Europe, where some models project lower, or even

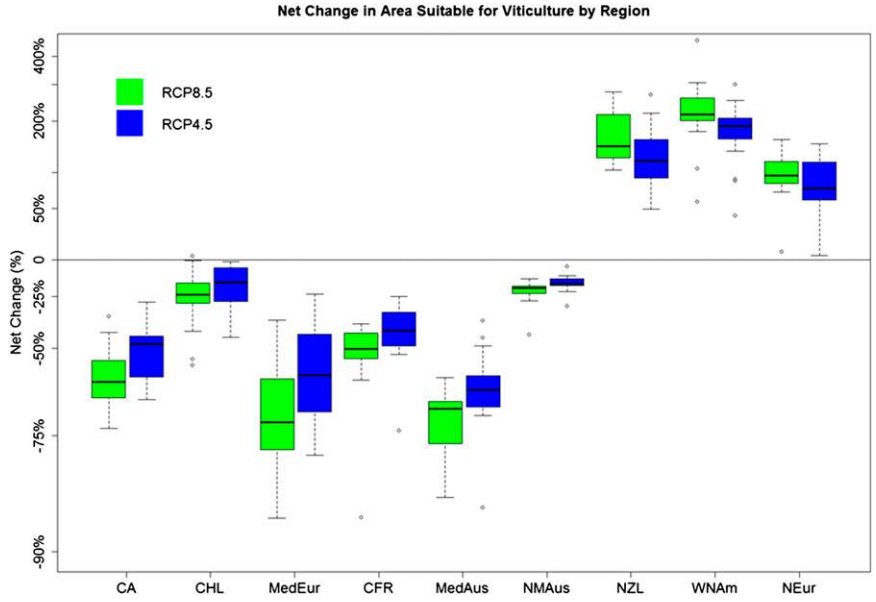

Fig. 2. Net viticulture suitability change in major wine-producing regions. Box plots show median values and quantiles of change in area suitable for viticulture projected by 17-member model ensemble for RCP 8.5 (green) and RCP 4.5 (blue). Mediterranean-climate wine-producing regions show declines, whereas New Zealand, western North America, and Northern Europe show substantial increases in suitable area (note that vertical axis is log-transformed). CA, California floristic province; CFR, Cape floristic region (South Africa); CHL, Chile; MedAus, Mediterranean-climate Australia; MedEur, Mediterranean-climate Europe; NEur, Northern Europe; NMAus, non–Mediterranean-climate Australia; NZL, New Zealand; WNAm, western North America. Fig. S5 provides regional definitions.

decreasing, change in footprint dependent on the degree of northward shift projected by a GCM.

Water use for viticulture may increase in traditional wine growing areas, as vineyards use water for misting or sprinkling to reduce grape temperatures on the vine to adapt to climate change. The area of intersection of projected decrease in viticultural suitability (an index of potential need for water for irrigation or grape cooling), projected decrease in precipitation, and preexisting high water stress within each region provides an index of the potential for freshwater conservation impacts [Freshwater Impact Index (FII); Table 2]. The ensemble average of this index is highest in Chile at 43% under RCP 8.5, and near or in excess of 25% in California, Mediterranean Europe, and the Cape of South Africa. Mediterranean Australia has a relatively low index value as a result of low historical levels of surface water withdrawal as a proportion of runoff, despite recent droughts.

Two examples from Chile and western North America illustrate issues of water use and potential habitat loss. Chile is likely to experience among the greatest freshwater impacts in Mediterranean-climate growing regions. By 2050, a majority of the premium wine-producing valleys in Chile (Maipo, Cachapoal, and Colchagua) will become mostly unsuitable under RCP 8.5, and the suitability of other regions (Aconcagua and Maule) are projected to decline considerably, leading to possible water use for grape cooling and heightened need for irrigation as a result of precipitation decreases. Strain on water resources is already high in the region, with 95% of the area currently suitable for viticulture already under water stress, the highest of any of the Mediterranean-climate wine-growing regions. The projected mean precipitation decrease of 15.5% (RCP 8.5; lower quartile, −21; upper quartile, −10; Table 2), coupled with potential depletion of glacial meltwaters, will likely exacerbate water stress. Indeed, most of central Chile's agricultural activities depend on water derived from snowmelt-dominated basins, which are particularly vulnerable to climate change, as they will be affected by changes in temperature and precipitation. Precipitation in the Maipo Valley, one of the most important wine-producing valleys in Chile, is projected in an independent estimate to decrease by approximately 20% by 2050 (29). This decrease, coupled with an average temperature increase of 3 °C to 4 °C in the catchment area, will affect river discharges and seasonality (30). Similarly, other major wine-producing valleys (e.g., Aconcagua, Maule)

Table 1. Ecological footprint of viticulture 2050, RCP 8.5

2050 RCP 8.5	Net change in area suitable for viticulture, mean % (quantiles)	Ecological footprint 2000, % area (ha × 10^6)*	Ecological footprint trend to 2050, % mean change (quantiles)
California	−60 (−42, −55, −66, −73)	29.8 (2.8)	10 (2, 5, 11, 27)
Chile	−25 (0, −17, −29, −55)	0.8 (0.05)	0 (−38, −25, 38, 50)
Mediterranean Europe	−68 (−39, −61, −78, −86)	2.4 (1.8)	342 (125, 263, 392, 525)
Cape floristic region	−51 (−41, −44, −54, −66)	46.0 (2.5)	14 (9, 11, 15, 19)
Australia (Med)	−73 (−61, −67, −76, −87)	44.0 (15.1)	−5 (−16, −8, 0, 6)
Australia (non-Med)	−22 (−15, −19, −23, −31)	40.9 (13.8)	2 (0, 2, 5, 11)
Northern Europe	99 (58, 83, 118, 149)	1.1 (2.5)	191 (−10, 10, 291, 618)
New Zealand	168 (104, 124, 216, 264)	6.6 (0.1)	126 (98, 103, 152, 174)
Western North America	231 (96, 201, 259, 338)	44.1 (4.9)	16 (2, 12, 23, 28)

Ensemble means are shown with quantiles shown in the order 5%, 25%, 75%, and 95%. RCP 4.5 values are given in Table S1. Med, Mediterranean climate; non-Med, non-Mediterranean climate.

*Ecological footprint is the percentage of suitable viticulture area that intersects with natural lands as defined by HII < 10 (27).

Table 2. Potential freshwater conservation impact of viticulture under climate change, 2050 RCP 8.5

2050 RCP 8.5	Decline in area currently suitable for viticulture, mean % loss (quantiles)*	Existing water stress, mean % area†	Precipitation trend to 2050, mean % change (quantiles)	Freshwater Impact Index (FII), 2050, mean % area (quantiles)
California	70 (50, 64, 77, 83)	85.9	−2.0 (-26.5, −10.8, 4.2, 16.2)	31.3 (0, 2, 61, 71)
Chile	47 (23, 35, 59, 81)	94.6	−15.5 (−29.3, −21.4, −9.8, −0.8)	43.0 (10, 24, 62, 80)
Mediterranean Europe	85 (54, 80, 96, 100)	50.7	−8.4 (−20.4, −11.8, −4.1, −0.1)	39.1 (5, 14, 20, 22)
Cape floristic region	55 (45, 48, 58, 70)	44.9	−9.8 (−22.4, −10.8, −5.0, −3.1)	24.3 (16, 22, 27, 30)
Australia (Med)	74 (62, 69, 78, 88)	3.0	−10.6 (−18.5, −15.8, −4.5, 11.6)	1.7 (0, 2, 2, 3)
Australia (nonMed)	46 (36, 37, 50, 59)	34.6	−1.5 (−11.2, −6.0, 2.0, 10.7)	14.2 (0, 8, 22, 26)
Northern Europe	84 (48, 74, 98, 100)	17.2	−3.0 (−10.6, −7.1, −0.1, 5.8)	16.3 (5, 14, 20, 22)
New Zealand	17 (0, 10, 23, 33)	0.0	−1.2 (−8.1, −3.7, 1.3, 4.7)	0 (0, 0, 0, 0)
Western North America	59 (34, 52, 72, 78)	23.7	−0.4 (−9.5, −4.9, 3.5, 9.0)	13.8 (0, 7, 21, 27)

Ensemble means are shown with quantiles shown in the order 5%, 25%, 75%, and 95%. RCP 4.5 values are given in Table S1.

*Decline in area currently suitable for viticulture values indicate areas in which conditions for producing high quality wine grapes will be declining, leading to the need for possible adaptation measures such as irrigation or misting of grape clusters to control temperature.

†Existing water stress is the proportion of area suitable for viticulture with WSI >0.2 (25).

‡FII is the percentage of suitable viticulture area that meets the three criteria of suitability decline by 2050, projected decline in precipitation by 2050, and existing WSI >0.2.

will also show a decrease in available water discharge ranging between 20% and 30% by 2050 (30, 31). The increasing demand on water resources will place Chile's freshwater ecosystems at risk.

Western North America has the greatest area of increasing ecological footprint, especially in the Rocky Mountains near the Canadian/US border. The conservation effort most likely to be impacted by changing wine suitability in this region is the Yellowstone to Yukon (Y2Y) initiative, a multiagency, multiorganization effort to provide habitat linkages for large and wide-ranging mammal species such as grizzly bear (*Ursus arctos*), gray wolf (*Canis lupus*), and pronghorn (*Antilocapra americana*) from Yellowstone National Park north to the Yukon Territory in Canada (32). Vineyards are already rapidly expanding in nearby areas of the Columbia River basin of eastern Washington, the Snake River valley of Idaho, and the Okanagan Valley in British Columbia (33). Future suitability for wine grapes within the Y2Y planning area is expected to increase by a factor of 19 by 2050 (Fig. S2). Ex-urban development with associated residential or artisanal vineyards may act in synergy with changes in wine suitability. Since 1940, parts of the Canadian Rockies and western Montana have experienced some of the highest decadal housing growth rates (more than 400%) within 50 km of a protected area (34). Similar housing growth in the Napa Valley of California has been associated with extensive development of small-estate vineyards. Large-lot housing may be compatible with movements of animals such as pronghorn and wolves, but vineyards almost certainly would not (18, 19). Vineyards currently in these areas are routinely fenced to exclude herbivores such as deer and elk and omnivores such as bear (35). Maintaining the goals of Y2Y may therefore require proactive land acquisition to minimize incompatible vineyard development within wildlife-rich areas or important migration routes.

Uncertainties in our estimates of viticulture suitability change and its conservation consequences arise from climate models, concentration pathways, wine suitability models, and estimates of water stress and habitat condition. The causes for these uncertainties are diverse, including scientific and socioeconomic factors. However, because our impact models are driven by individual GCMs, we are able to quantify much of the uncertainty arising from climate modeling and concentration pathways and document broad areas of model agreement. For instance, 168 of 170 impact models agree across five regions and two concentration pathways that Mediterranean climate growing regions will experience a decrease in viticultural suitability, and all models agree in projecting increasing suitability for Northern Europe, western North America, and New Zealand (Fig. 2). Within these broad areas of agreement, larger decreases in currently suitable areas and larger increases in novel area are projected under the higher concentration pathway (RCP 8.5). Among suitability models, the largest changes are seen in the temperature varietal model, and this model is most sensitive to the temperature increases in the higher concentration pathway. All ensemble members project all areas will experience increase in ecological footprint, with the exceptions of Chile, Mediterranean Australia, and Northern Europe, where there is less model agreement (Table 1 quantiles).

Frontiers for additional research are suggested by several of our results. Wine production in tropical montane areas projected as suitable for viticulture—at present and in the future (Fig. 1 and Fig. S1)—currently contribute little to global wine production because these regions lack long summer days and cool nights for the maturation of high-quality wine grapes. However, increasingly sophisticated manipulation of sugar and chemical composition in winemaking may overcome this limitation, creating conservation concerns in these high biodiversity areas. Similarly, China is not known for its European-style wines, but it is among the fastest growing wine-producing regions in the world. It has significant areas suitable for viticulture (Fig. 1), and these areas are in the same mountains that are habitat for the giant panda (*Ailuropoda melanoleuca*). Future conservation efforts for the giant panda need to incorporate consideration of viticulture as a potential land use and viticultural suitability trends in response to climate change.

Discussion

Global changes in suitability for wine production caused by climate change may result in substantial economic and conservation consequences. Redistribution in wine production may occur within continents, moving from declining traditional wine-growing regions to areas of novel suitability, as well as from the Southern Hemisphere to large newly suitable areas in the Northern Hemisphere. The actual extent of these redistributions will depend on market forces, available adaptation options for vineyards, and continued popularity of wine with consumers. Even modest realization of the potential change could result in habitat loss to viticulture over large areas.

The ranges of plants and animals are likely to move in response to climate change, at the same time that wine suitability is changing. Vineyards may move faster than wild species, as they are moved through human action independent of contiguous habitat or natural dispersal processes. New vineyard establishment anticipating improving conditions may leapfrog intervening areas, whereas wildlife and especially plant species will have to follow suitability based on natural dispersal and remaining habitat. We know that species move individualistically in response to climate change (36), so the movement of species of conservation interest may occur at different paces relative to shifts in vineyards. For example, some large mammals in the Y2Y may move north to track cool climates, whereas others may remain resident in

regions of increasing wine grape suitability. Assessing conservation impacts of changing wine suitability therefore requires detailed regional analysis. We have identified some regions where large potential loss of habitat and increased pressure on highly stressed freshwater systems suggest that such analysis is a high priority.

Our conclusions about global suitability change and possible conservation impacts of changing viticulture are supported by strong model agreement in our impact ensemble (Fig. 2), but subject to important spatial and temporal refinements. Local soil composition and topography will strongly influence the local manifestation of the global patterns (37). Calculating impacts on viticultural suitability by using daily extreme temperatures may yield different results than the 20-y mean monthly climatologies used here (11, 38, 39). Other studies that have used extreme daily temperatures show more pronounced changes in the projected range of viticultural suitability than the results presented here (11, 38, 39). Therefore, our findings may be conservative. Growing degree day (GDD) estimates based on daily values may produce slightly different estimations of suitability than the GDD summation calculated from monthly means (11, 38, 39). Lower greenhouse gas concentrations (as in RCP 4.5) produce lesser decreases in current wine-producing regions and moderate the amount of newly suitable area (Table S1), indicating that international action to reduce greenhouse gas emissions can reduce attendant impacts on viticulture and conservation.

Wine grapes are symbolic of a wide variety of crops whose geographic shifts in response to climate change will have substantial implications for conservation. Although changes in suitability for viticulture may be especially sensitive to climate and therefore among the first to occur, other crops have well-known climatic limits and are expected to experience change as well (15, 40). The interactions between crop suitability and conservation are not one-way interactions, as consumer preference for environmentally friendly production may penalize commodities that have novel or disproportional impacts on nature. The literature on indirect impacts of climate change on conservation is growing, including, for instance, the potential conservation impacts of human populations displaced by sea level rise (41). Indirect impacts of change in agriculture on ecosystems and their services has an important place in this growing body of research (15)

Adaptation strategies are available to wine growers to maintain productivity and quality as well as to minimize freshwater withdrawals and terrestrial footprint (39). Integrated planning for production and conservation is emerging in several prominent wine-producing regions. In the Cape region of South Africa, wine producers and conservationists have joined together in the Biodiversity and Wine Initiative (42). This industry-led effort has included joint planning of vineyard expansion to avoid areas of high conservation importance. It has produced a marketing campaign with an environmental theme. Participants are examining new management practices to reduce the environmental footprint of vineyards. Continued development and adoption of similar programs that emphasize climate change adaptation for wine production (e.g., the Vinecology initiative, and the Wine, Climate Change and Biodiversity Program in Chile) will jointly benefit the industry, consumers, and conservation (43).

Investment in new varieties that would give similar flavors but with altered climate tolerances may be an important investment for the industry and for conservationists wishing to avoid unfavorable land or water use outcomes. Marketing in anticipation of change can build consumer interest in new varietals. Decoupling traditional varieties from regional appellations is an alternative to attempting to maintain varieties in regions in which their suitability is declining. This "managed retreat" to new varieties may reduce water use and upland habitat loss that might be associated with attempts to retain varieties. Identification of wine by varietal (e.g., Pinot Noir), as is common outside of Europe, may therefore be more adaptive than identification by geographic origin (e.g., Bordeaux).

Vineyard management is another arena in which adaptation innovation may benefit conservation. Improved cooling techniques such as water-efficient micromisters or strategic vine orientation/trellising practices to control microclimates at the level of individual grape clusters can greatly reduce water use demands (44). Increases in water use may be limited, at least in the near term, in areas where irrigation is traditionally avoided as a result of custom or regulation (e.g., parts of Europe) (25). At the same time, these policies will render adaptation to climate change more difficult. Chile and California are areas with traditions of irrigation (26) and high Freshwater Impact Index values, indicating that their freshwater habitats may be most at risk as a result of climate change impacts on vineyard water use. Adaptation strategies involving viticulture, vinification, marketing, land use planning, and water management can all help avoid conflicts with conservation objectives in areas of declining as well as expanding suitability.

A growing and increasingly affluent global population will likely create an increasing demand for wine and ensure that wine grapes will be grown in current wine-producing areas to the extent that available land and water will allow, as well as expand into new areas, including natural habitats important for their ecosystem services. Freshwater habitats may be particularly at risk where climate change undermines growing conditions for already established vineyards. Climate change adaptation strategies that anticipate these indirect impacts are particularly important for creating a future that is positive for vintners, wine consumers, and ecosystems alike. Alternatives are available that will allow adaptation in vineyards while maintaining the positive ecological association that is valued in the industry. In wine production, as with the production of other agricultural commodities, the United Nations Framework Convention on Climate Change goals of maintaining sustainable development and allowing ecosystems to adapt naturally can be achieved only if adaptation includes consideration of secondary impacts of agricultural change on ecosystems and biodiversity.

Materials and Methods

Climatologies. For current (i.e., 1961–2000) climate, we used the WorldClim global climate dataset on a 2.5 arc-minute grid (45). For future climate projections, we used GCMs from the fifth phase of the Coupled Model Intercomparison Project (CMIP5). Future global climatologies, representing monthly 20-y normal values for 2041 to 2060, were downscaled from the native resolution of 17 GCMs (Table S2) under the RCP 4.5 and RCP 8.5 concentration pathways. The GCMs were downscaled by computing the difference between the average climate for modeled future climate scenario and the current climate computed by the same GCM. We then used smooth splines to interpolate these differences to a higher spatial resolution. Finally, we applied these differences to a high-resolution estimate of the current climate (WorldClim) such that all datasets are bias-corrected in the same manner (46). Bias correction has been shown to be important in climate change analyses of wine grape suitability (38).

Suitability Models. The consensus suitability model used here is an impact model constructed from the area of agreement of three independent modeling methods—a temperature-varietal model, a heat summation phenology model, and a multifactor distribution model—that reflect a range of wine suitability modeling techniques suggested in the literature that are implementable by using standard 20-y monthly climate normals. Consensus models have been shown to be more robust than individual models in bioclimatic modeling (24), and testing shows this to be the case with our consensus suitability model (Fig. S3 and Table S3).

For the temperature–varietal model, optimal average growing season temperatures for 21 common wine grape varieties were used as defined by Jones et al. (4). The phenological method is adapted from Hayhoe et al. (47), in whose work viticulture suitability is determined by biophysical response as ripening progresses. The multifactor model was implemented using the MaxEnt (Maximum Entropy) species-distribution model, which produces a model of climatic suitability for a species at any location and time period based on known occurrences (Fig. S4) and present and future environmental variables (Table S4) (48, 49). *SI Materials and Methods* includes a full description of each suitability model. Minimum annual temperature (>−15 °C) and annual precipitation (between 255 mm and 1,200 mm) limiting values were used to constrain individual suitability models (3).

Ecological Footprint. We used the Human Influence Index (HII) (27) to assess the area of natural habitat impacted by viticulture (present and future). This 1-km spatial resolution global dataset integrates human impact-related variables such as population density, proximity to road, proximity to railroad, nighttime light, and urban/agricultural land uses to provide a continuous

score of habitat integrity (27). We transformed the HII into a binary index of natural/nonnatural habitats by using an HII score of <10 that agrees with independent estimates of natural habitat remaining in global biodiversity hotspots (12), and measured the intersection of natural lands with viticultural suitability in each of our two time periods (Fig. S5 and Table S5 provide details on regions of analysis and HII threshold selection).

Water Stress Index. Current water stress index (WSI) data (Table 1) were generated by the WaterGAP2 model (28) as presented in ref. 50. WSI is the ratio of aggregate domestic, industrial, and agricultural demand to runoff in a given watershed (50). A watershed is considered to be under water stress at WSI > 0.2 (50).

Freshwater Impact Index. We define the FII as the intersection of decrease in current viticulture suitability, projected mean decrease in precipitation between 2000 and 2050 in our 17-GCM ensemble, and area of water stress (WSI > 0.2) (51). Decrease in current viticulture suitability indicates areas in which water use may be required for irrigation or grape cluster cooling to adapt to climate change.

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Supporting Information

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SI Materials and Methods

Viticulture Suitability Models. We use three viticulture suitability models, representing each of three broad classes of suitability models that have been proposed in the literature using long-term mean climatic projections: (*i*) average growing season temperatures (e.g., refs. 1, 2), (*ii*) phenology (e.g., refs. 3–6), and (*iii*) multiple variables (e.g., refs. 7–10). For the temperature approach, we have chosen average temperature during the growing season, the most commonly applied temperature model. To represent the phenological approaches, we use growing degree day (GDD) accumulation, the most often used of this category (e.g., refs. 3–5). We used MaxEnt (Maximum Entropy), a widely used climate-distribution model (also known as species distribution model, niche model, or bioclimatic envelope model) to represent multiple variable models because of its broad application and well-documented methods. Our implementation of each of these three suitability models is described in the subsequent sections.

Method 1: Temperature—average temperature during growing season. Optimal average growing season temperatures for 21 common varietals of wine producing *Vitis vinifera* were used as defined by Jones et al. (1). Taken together, the optimal range for all common varietals spans average growing season temperatures from 13.1 °C to 20.9 °C (see table below). Areas falling within this range during the growing season were considered suitable. Growing season was defined as April to October in the Northern Hemisphere and October to April in the Southern Hemisphere. Areas experiencing mean monthly minimum temperatures lower than −15 °C at any time during the year or mean precipitation greater than two SDs from the mean of surveyed wine growing areas were excluded (see below for details).

The following table shows variety mean growing season temperature bands from Jones et al. (1).

Variety	Low temperature, °C	High temperature, °C
Muller-Thurgau	13.1	15.05
Pinot Gris	13.1	15.3
Gewurztraminer	13.1	15.65
Pinot Noir	14	16.2
Chardonnay	14.05	17.15
Sauvignon Blanc	14.65	17.7
Riesling	13.2	17.1
Semillon	14.9	18.15
Cabernet Franc	15.35	18.9
Tempranillo	15.9	18.6
Dolcetto	16.4	18.55
Merlot	16	18.8
Malbec	16.25	18.95
Viognier	16.6	18.8
Syrah	16.15	19.15
Cabernet Sauvignon	16.4	19.85
Sangiovese	16.9	19.5
Grenache	16.6	20.1
Carignane	17.15	20.2
Zinfandel	17.5	20.5
Nebbiolo	17.6	20.9
All varieties	13.1	20.9

Method 2: Phenology—GDD maturity groupings. The phenological method is adapted from Hayhoe et al. (5), and in this model, viticulture suitability is determined by biophysical response as ripening progresses. Ripening time is determined by summing the biologically active GDDs greater than a temperature threshold of 10 °C. Wine grape varietals are assembled into eight distinct groups depending GDD required for maturity/ripening after the work of Gladstones (4). In each grid cell, GDD is summed by using mean monthly temperature until the maturity threshold is reached for a given maturity grouping. The monthly cumulative GDD of a given location (i.e., pixel) was calculated as the product of the mean monthly temperature greater than the 10 °C threshold and the number of days in the month (Eq. **S1**).

$$\mathrm{GDD10}_{\mathrm{month}} = [(\mathrm{TMax}_{\mathrm{month}} + \mathrm{TMin}_{\mathrm{month}})/2 - 10] \ * \ \mathrm{Days}_{\mathrm{month}} \quad \textbf{[S1]}$$

The average temperature for the month in which the threshold from the list below is reached is then used to determine suitability where 15 °C to 22 °C is considered "optimal," 22 °C to 24 °C is considered "marginal," and >24 °C is considered "impaired" (4, 5).

A location was deemed suitable if at least one of the eight maturity groupings was optimal (e.g., 15–22 °C in month GDD threshold is reached). Minimum annual temperature and annual precipitation constraints, identical to those used in the average temperature of growing season method, were applied. The GDD thresholds used were: 1050, 1100, 1150 (e.g., Pinot Noir, Chardonnay, Sauvignon Blanc), 1200 (e.g., Malbec, Zinfandel, Reisling), 1250 (e.g., Merlot, Cabernet Franc, Viognier), 1300 (e.g., Cabernet Sauvignon), 1350 and 1400, as defined in ref. 4.

For example, a varietal from group 1 would mature with 1,050 GDD. If that GDD threshold is achieved in August, the monthly mean temperature from August would be selected, and, if, for instance, that temperature was 21 °C, the condition for that varietal would be considered optimal. The process would be repeated for all varietals, and the number of optimal scores recorded. If any varietal scored as optimal, the location (i.e., pixel) would be graded as suitable. If no varietal scored as optimal, the location would be graded as unsuitable.

Method 3: Multiple variables—MaxEnt. The MaxEnt climate-distribution model takes as input a set of layers or environmental variables (e.g., elevation, precipitation), as well as a set of occurrence locations, and produces a model of climatic suitability for a species (7). We used this approach to model suitable climate space for cultivation of *V. vinifera*. Occurrence points ($N = 1{,}129$) for viticulture were derived from a georeferenced global dataset of known viticulture sites (11).

The bioclimatic predictor variables used in MaxEnt modeling were as follows (also see Table S4):

- Average temperature in growing season;
- Total precipitation in growing season;
- Precipitation seasonality (coefficient of variation);
- Total GDD (growing degree days above 10 °C) in growing season;
- Mean maximum temperature of the warmest month during growing season;
- Mean minimum temperature of the coldest month during growing season;
- Mean diurnal range (mean monthly maximum − minimum);
- Mean minimum temperature of the coldest month; and
- Total annual precipitation.

Table S4 gives information regarding the relative importance of the chosen bioclimatic variables in producing the MaxEnt models.

The MaxEnt software establishes a relationship with existing climate for the aforementioned parameters at known occurrence points, then projects this relationship onto a map of future climate for each global climate model (GCM)/Representative Concentration Pathway (RCP) combination. Results for current and future climates are a continuous value from 0 to 1, reflecting the strength of the relationship between known viticulture occurrence and the combination of climate parameters that exists in a given pixel. To convert the continuous value projection to a binary presence/absence distribution, we applied the maximum sensitivity plus specificity logistic threshold (12) on the average values produced by 10 model replicates. Additional discussion of MaxEnt methods is provided by Elith et al. (13).

No temperature or precipitation constraints were applied, as minimum annual temperature and annual precipitation were included as predictor variables.

Minimum temperature and precipitation constraints. At the northern boundaries of wine-growing regions, chilling stress during growing season and overwinter minimum temperatures are limiting factors in determining viticulture suitability (3, 4, 14). Overwinter cold hardiness of *V. vinifera* varies according to age of the vine, variety, and seasonal timing of annual minimum temperatures (14, 15). However, temperatures below −12 °C impart tissue damage that can impair production, and temperatures below −25 °C are lethal to most varieties (14–16). To create a conservative threshold for excess risk of tissue damage as a result of extreme cold, areas with mean minimum temperature of the coldest month <−15 °C were classified as unsuitable for viticulture (16, 17).

Too much or too little precipitation can make a region unsuitable for growing high-quality wine grapes (3, 4, 14). Overly watered areas are prone to excess vigor and/or fungal pathogens, whereas arid areas require irrigation infrastructure to achieve the annual water requirements of the vines. We compiled annual precipitation data for global wine regions (N = 135) as documented by Gladstones (4) and Johnson and Robinson (18). We used mean annual precipitation of these regions ±2 SDs as upper and lower bounds of annual precipitation in determining wine-growing suitability. Under this definition, areas with >1,226 mm and <200 mm of precipitation were used as constraints defining areas as unsuitable for viticulture.

Climate Change Scenarios. For current climate, we used the WorldClim global climate dataset on a 2.5 arc-minute grid (19). Current climate was defined as the reference period 1971 to 2000 and all parameters used are monthly or annual means. (WorldClim climatologies are available for download at www.worldclim.org.) Future global climatologies, representing monthly 20-y normals for 2041 to 2060, were downscaled from the native resolution of 17 Coupled Model Intercomparison Project (fifth phase)-era GCMs (see Table S1 for list) under the RCP 4.5 and RCP 8.5 concentration pathways. These future climatologies are now available on WorldClim as well. The GCMs were downscaled by computing the difference between the average climate for modeled future climate scenario and the current climate computed by the same GCM. We then used smooth splines to interpolate these differences, to the higher spatial resolution (2.5 arc-minute) used in this analysis. Finally, we applied these differences to the WorldClim high resolution estimate of the current climate such that all datasets are bias corrected in the same manner (20). Bias correction has been shown to be important in climate change analyses of wine grape suitability (21).

Consensus Suitability Outputs. The modeled distribution of viticulture produced for every time period and GCM/RCP combination presented in Fig. 1 and used for all subsequent analysis presented in Table 1 and Table S1 represents the consensus agreement (i.e., union) of all three viticulture suitability models. This has the effect of constraining modeled distribution to the areas that are in greatest agreement among all 51 suitability model/GCM combinations (Fig. S1).

Ecological Footprint. Human influence scoring used in this analysis was developed by Sanderson et al. (22). This dataset provides 1-km-resolution global coverage of a Human Influence Index (HII). HII scores are a spatially explicit summation of human impact variables such as population density, proximity to road, proximity to railroad, nighttime light sources, and urban/agricultural land uses. A HII score of 0 suggests zero human influence whereas a score of 64 implies maximum human impact. Sanderson et al. (22) provided a full description of HII methodology.

We transformed the HII into a binary index of natural/non-natural habitats by using an HII score <10. We then measured the intersection of the HII binary index with consensus suitability output for current climate and each GCM/RCP combination. Although the choice of HII threshold affects the calculated ecological footprint (Table S5), the HII <10 threshold best agrees with independent estimates of natural habitat remaining in global biodiversity hotspots (23). To capture the full detail of the high-resolution HII dataset, we resampled the 2.5 arc-minute grids of the viticulture suitability to the finer 30 arc-second resolution of the global HII data.

Water Stress Index. Current water stress index (WSI) data (Table 2) were generated by the WaterGAP2 model (24) as presented by Pfister et al. (25). WSI values in the work of Pfister et al. (25) are aggregated by watershed (i.e., each watershed has one unique value). WSI as presented in these sources is the ratio of aggregate domestic, industrial, and agricultural demand to runoff in a given watershed. A watershed is considered to be under water stress at WSI >0.2 (25, 26). WSI values for individual wine-growing regions were obtained by sampling the Pfister et al. WSI data (25) at each pixel that is suitable for viticulture. Aggregate WSI values presented in Table 2 are the mean values across all suitable pixels in a region for current and future time periods and for each individual GCM.

Freshwater Impact Index. We define Freshwater Impact Index (FII; Table 1 and Table S1) as areas with (*i*) decrease in current viticulture suitability, (*ii*) projected mean decrease in precipitation between 2000 and 2041 to 2060 in our 17-GCM ensemble, and (*iii*) existing WSI >0.2. Decrease in current viticulture suitability (Fig. 1, red) indicates areas in which water use may be required for irrigation or grape cluster cooling to adapt to climate change. Wine-growing regions that are already water-stressed and projected to experience decreases in precipitation are considered vulnerable to heightened ecological stress on aquatic ecosystems. Aggregate FII scores for each region presented in Table 1 and Table S1 represent the percentage of existing suitable viticulture area that meets all three of the aforementioned criteria.

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21. Diffenbaugh NS, Scherer M (2012) Using climate impacts indicators to evaluate climate model ensembles: Temperature suitability of premium winegrape cultivation in the United States. *Climate Dynamics* 40(3–4):709–729.
22. Sanderson EW, et al. (2002) The human footprint and the last of the wild. *Bioscience* 52(10):891–904.
23. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* 403(6772):853–858.
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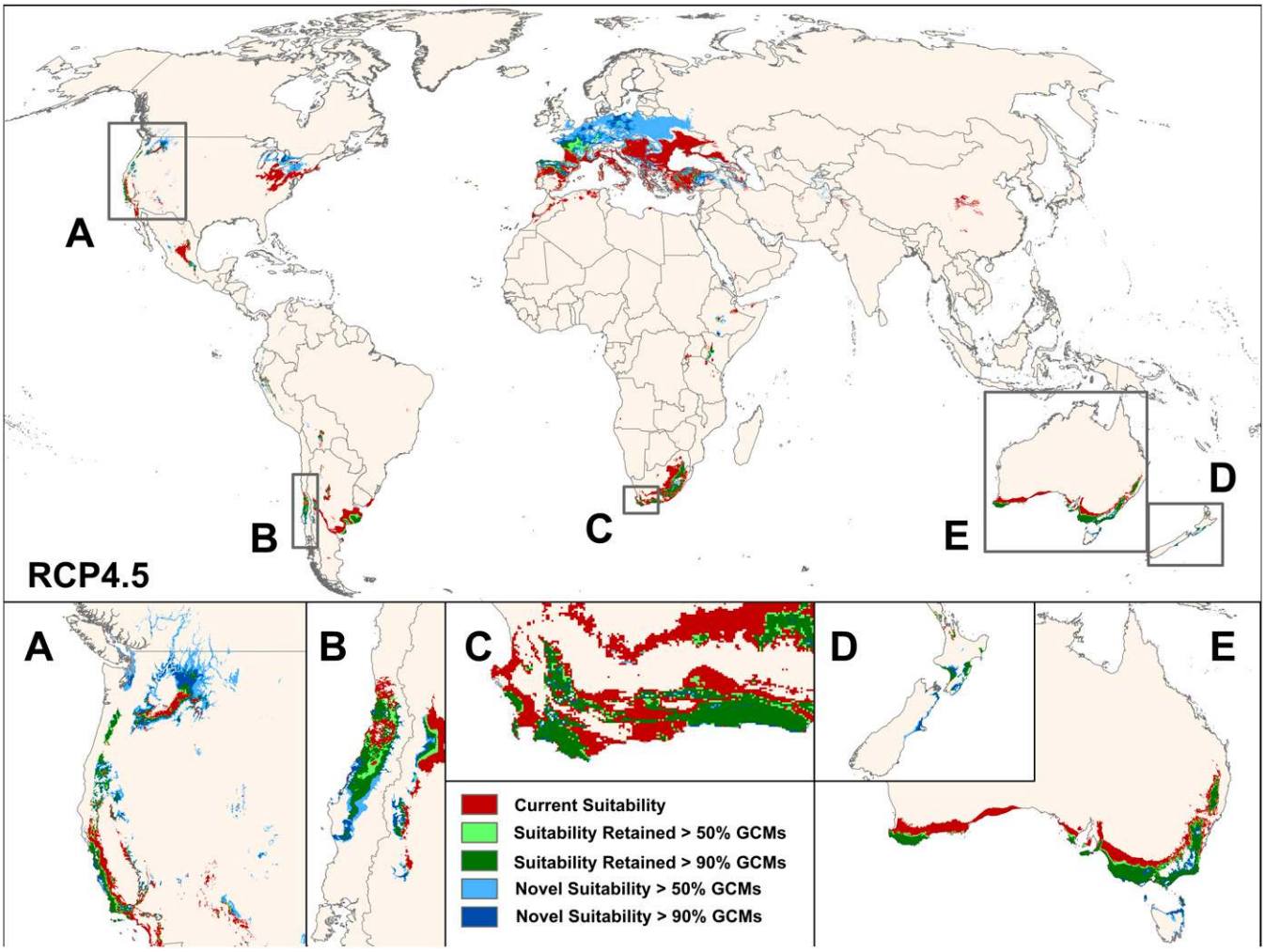

Fig. S1. Global change in viticulture suitability per RCP 4.5. Change in viticulture suitability is shown between current (1971–2000) and 2050 (2041–2060) time periods, showing agreement among a 17-GCM ensemble. Areas with current suitability that decreases by midcentury are indicated in red (>50% GCM agreement). Areas with current suitability that is retained are indicated in light green (>50% GCM agreement) and dark green (>90% GCM agreement), whereas areas not suitable in the current time period but suitable in the future are shown in light blue (>50% GCM agreement) and dark blue (>90% GCM agreement). (*Insets*) Greater detail for major wine growing regions: California/western North America (*A*), Chile (*B*), Cape of South Africa (*C*), New Zealand (*D*), and Australia (*E*).

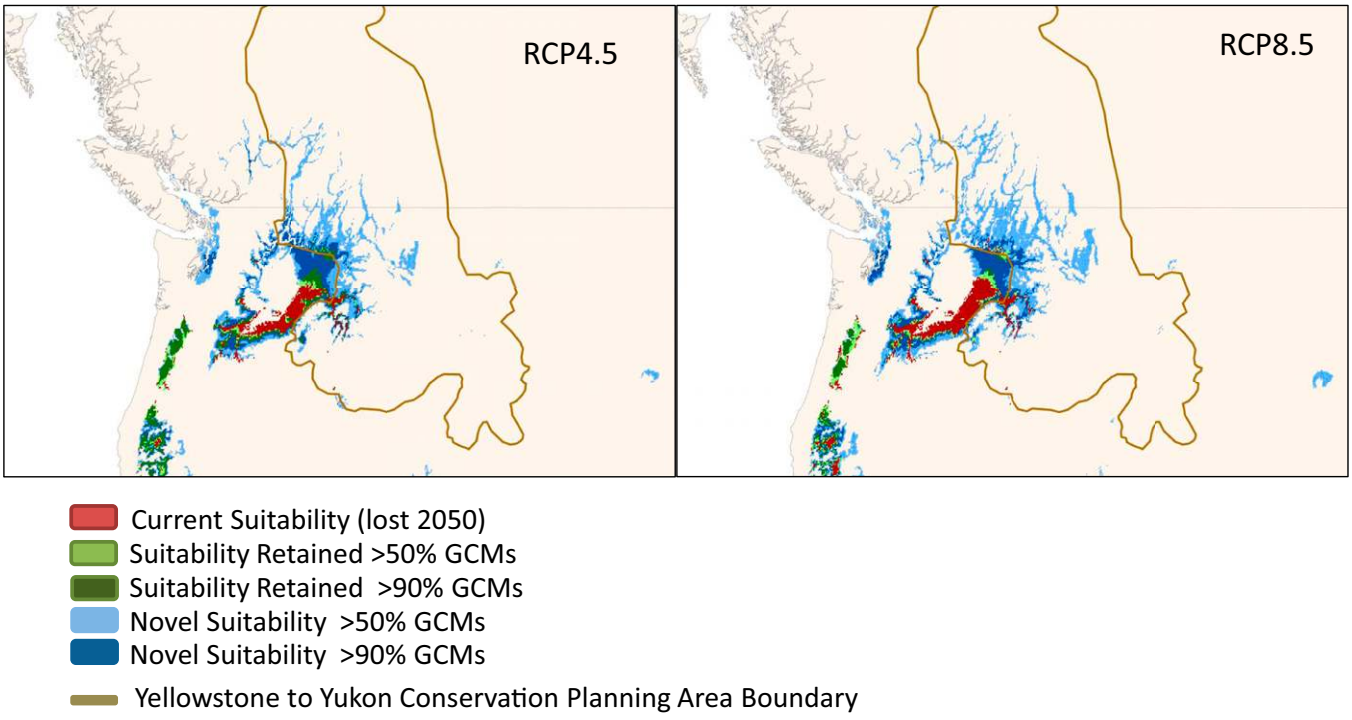

Fig. S2. Projections of 2050 viticulture suitability within the Yellowstone to Yukon Conservation Planning Area. Red indicates current suitability lost; light green indicates suitability retained for >50% GCMs; dark green indicates suitability retained for >90% GCMs; light blue indicates novel suitability >50% GCMs; and dark blue indicates novel suitability >90% GCMs. Brown outline shows Conservation Planning Area boundary. Area suitable for viticulture is projected to increase from ~680,000 ha to >9 million ha under RCP 4.5 and to >12 million ha under RCP 8.5 (increases of factors of 13 and 19, respectively).

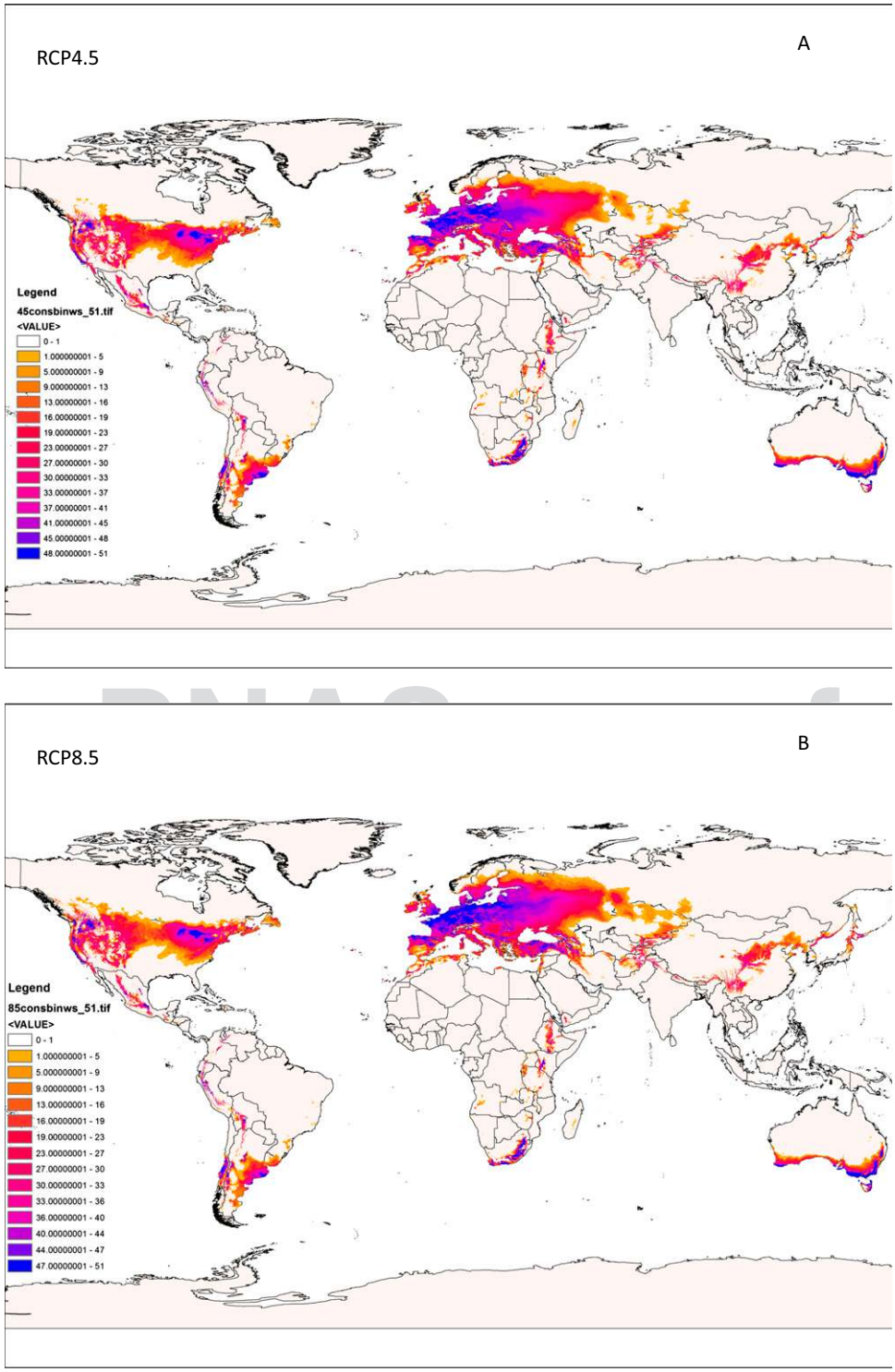

Fig. S3. Agreement among all 51 suitability model–GCM combinations (17 GCMs multiplied by three suitability models) for 2050 viticulture suitability. Color ramp shows full spread of individual model projections, with light yellow indicating little agreement and dark blue indicating universal agreement. Results presented in the manuscript generally comport to >90% agreement among individual suitability model–GCM combinations (purple and dark blue).

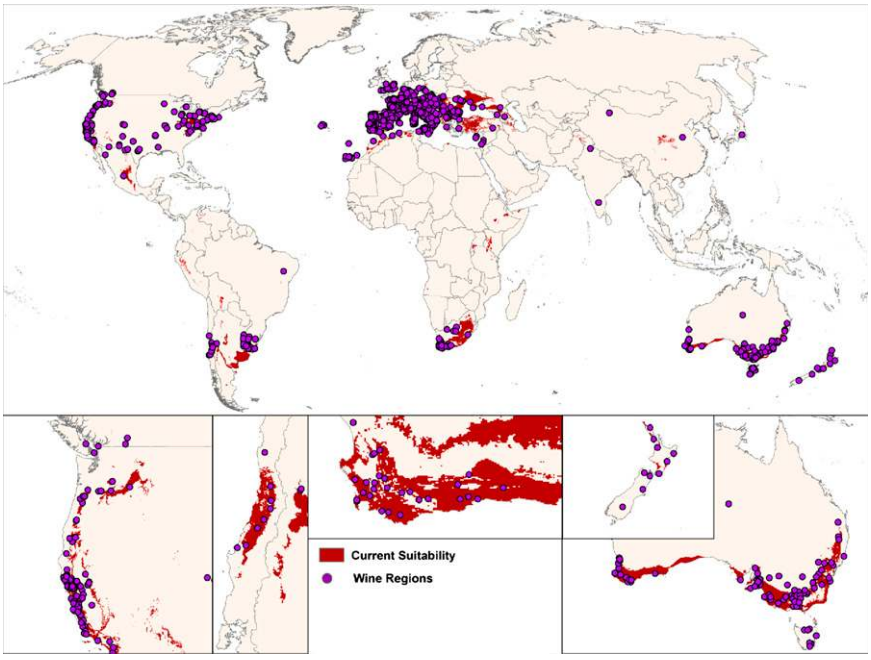

Fig. S4. Viticulture occurrence points used to produce the MaxEnt model of *Vitis vinifera* and to validate the model results.

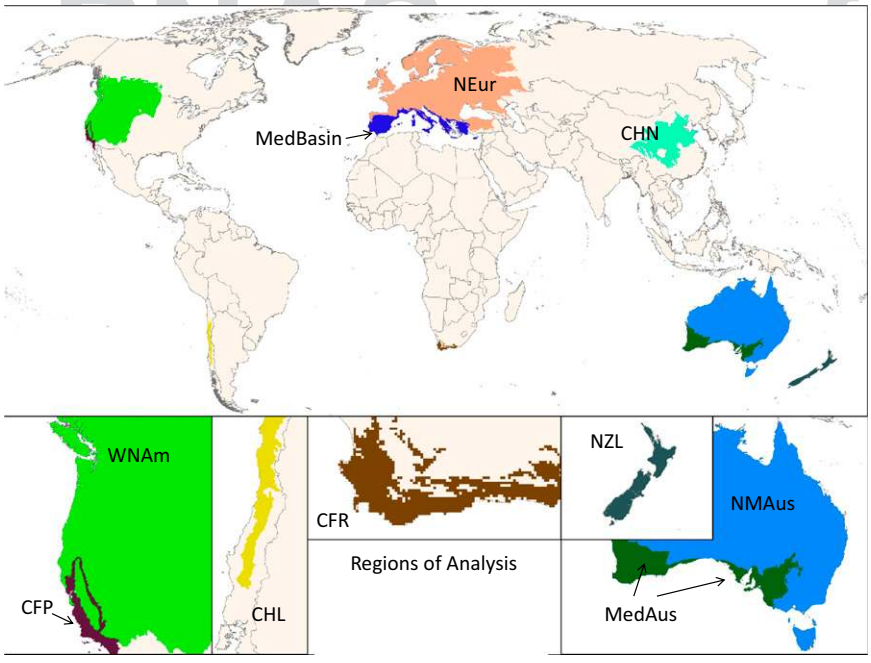

Fig. S5. Boundaries of the wine-producing regions used for the viticulture change analysis presented in Tables 1 and 2 and Table S2. Mediterranean climate regions are delineated from surrounding areas (e.g., California floristic province, Mediterranean basin, Cape floristic region, Chile, Mediterranean Australia) where possible, with boundaries conforming to World Wildlife Fund ecoregions within the Mediterranean forests, woodlands, and scrub biome.

Table S1. Ecological footprint and Freshwater Impact Index under climate change for prominent wine-growing regions, RCP 4.5

RCP 4.5	Net change in area suitable for viticulture, mean % (quantiles)	Ecological footprint 1971–2000, % area (ha × 10^6)*	Ecological footprint trend to 2041–2060, % change (quantiles)*	Decline in area currently suitable for viticulture, % mean (quantiles)†	Existing water stress, mean % area‡	Precipitation trend to 2041–2060, mean % change (quantiles)‡	Freshwater Impact Index, mean % (quantiles)§
California (CFP)	−52 (−29, −45, −60, −63)	29.8 (2.8)	8 (1, 4, 11, 16)	61 (36, 54, 71, 74)	85.9	−1.2 (6.3, 3.7, −11.8, −18.4)	24.0 (0, 11, 37, 62)
Chile (Med)	−19 (−4, −6, −28, −35)	0.8 (0.05)	0 (−25, −13, 13, 38)	38 (23, 28, 48, 58)	94.6	−14.7 (−0.1, −10.6, −20.9, −25.7)	33.6 (14, 28, 42, 59)
Mediterranean Europe	−58 (−29, −43, −70, −79)	2.4 (1.8)	258 (96, 154, 333, 433)	75 (40, 60, 89, 98)	50.7	−6.5 (−1.1, −4.3, −9.1, −13.6)	34.3 (15, 31, 40, 46)
Cape floristic region (South Africa)	−44 (−30, −36, −50, −55)	46.0 (2.5)	12 (4, 9, 13, 19)	48 (33, 42, 53, 60)	44.9	−6.4 (2.1, −2.6, −8.6, −15.8)	19.1 (5, 13, 26, 28)
Australia (Med)	−62 (−36, −57, −69, −84)	44.0 (15.1)	−3 (−12, −7, 0, 12)	63 (36, 56, 71, 85)	3.0	−9.1 (0.7, −5.2, −13.6, −19.2)	1.2 (0, 0, 2, 3)
Australia (non-Med)	−17 (−4, −14, −19, −31)	40.9 (13.8)	3 (−2, 0, 6, 10)	38 (26, 33, 45, 62)	34.6	−0.9 (7.8, 4.0, −5.9, −8.8)	9.7 (0, 4, 14, 23)
Northern Europe	+84 (+32, +60, +112 +137)	1.1 (2.5)	45 (−18, 0, 82, 155)	72 (27, 57, 92, 97)	17.2	−1.3 (3.9, 1.7, −4.1, −7.9)	11.8 (2, 9, 15, 18)
New Zealand	+135 (+73, +88, +178, +255)	6.6 (0.1)	117 (82, 102, 138, 150)	14 (2, 8, 22, 31)	0	−0.8 (4.0, 1.1, −3.6, −7.1)	0 (0, 0, 0, 0)
Western North America	+189 (+82, +148, +216, +301)	44.1 (4.9)	8 (−3, 2, 13, 22)	47 (25, 40, 53, 68)	23.7	−0.7 (3.9, 1.7, −3.4, −10.7)	12.2 (6, 10, 15, 18)

Ensemble means are shown where appropriate, with quantiles shown in the order 5%, 25%, 75%, and 95%. CFP, California Floristic Province; Med, Mediterranean; non-Med, non-Mediterranean.

*Ecological footprint is the percentage of suitable viticulture area that intersects with natural lands as defined by HII < 10 (27).

†Decline in area currently suitable for viticulture values indicate areas in which conditions for producing high quality wine grapes will be declining, leading to the need for possible adaptation measures such as irrigation or misting of grape clusters to control temperature.

‡Existing water stress is the proportion of area suitable for viticulture with WSI > 0.2 (25).

§FII is the percentage of suitable viticulture area that meets the three criteria of suitability decline by 2050 (2041–2060), projected decline in precipitation by 2050, and existing WSI > 0.2.

Table S2. List of GCMs and abbreviations used for analysis

Model Name	Modeling Center	Country
ACCESS1-0	CSIRO-BOM (Commonwealth Scientific and Industrial Research Organisation, Australia, and Bureau of Meteorology)	Australia
bcc-csm1-1	BCC (Beijing Climate Center, China Meteorological Administration)	China
CCSM4	NCAR (National Center for Atmospheric Research)	USA
CNRM-CM5	CNRM-CERFACS (Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique)	France
GFDL-CM3	NOAA GFDL(National Oceanic and Atmospheric Administration - Geophysical Fluid Dynamics Laboratory)	USA
GISS-E2-R	NASA GISS (National Aeronautic and Space Administration Goddard Institute for Space Studies)	USA
HadGEM2-AO	MOHC (Met Office Hadley Centre)	UK
HadGEM2-ES	MOHC (Met Office Hadley Centre)	UK
HadGEM2-CC	MOHC (Met Office Hadley Centre)	UK
inmcm4	INM (Institute for Numerical Mathematics)	Russia
IPSL-CM5A-LR	IPSL(Institut Pierre-Simon Laplace)	France
MIROC5	MIROC (Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies)	Japan
MRI-CGCM3	MRI (Meteorological Research Institute)	Japan
MIROC-ESM-CHEM	MIROC (Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies)	Japan
MIROC-ESM	MIROC (Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies)	Japan
MPI-ESM-LR	MPI-M (Max Planck Institute for Meteorology)	Germany
NorESM1-M	NCC (Norwegian Climate Centre)	Norway

All models are part of the Coupled Model Intercomparison Project (fifth phase) of the World Climate Research Program.

Table S3. Performance comparison among three suitability models used for this analysis

Model	cor(Production)	cor(Acreage)	AUC
Consensus	0.759	0.715	0.784
Majority (two of three)	0.710	0.667	0.901
Maxent	0.738	0.660	0.936
GDD	0.691	0.663	0.780
AvT	0.643	0.597	0.903

"cor" columns show Spearman rank order coefficient (compared with country level statistics for wine production and vineyard acreage) for each individual suitability model as well as majority (two of three model agreement) and consensus (three of three model agreement). "AUC" column shows the area under the receiving operating curve based on presence/absence values derived from the global viticulture dataset and 10,000 randomly generated pseudoabsence points. Maxent AUC value is generated from a 30% subset of viticulture occurrence points reserved for model testing. AUC, area under the curve.

Table S4. Bioclimatic parameters used in Maxent modeling

Variable	Mean contribution, %	Mean permutation importance
Mean temperature in growing season	7.2	1.4
Total precipitation in growing season	3.9	10.7
Precipitation seasonality (C of V)	5.6	4.7
Total GDD > 10 °C (iGDD10) in growing season	21.7	5.7
Mean maximum temperature of warmest month during growing season	1.2	4.6
Mean minimum temperature of coldest month during growing season	22.6	7.8
Mean diurnal temperature range (mean monthly maximum − minimum)	1.8	1.9
Mean minimum temperature of coldest month	28.4	44.4
Annual precipitation	7.6	18.7

Variables were selected as being biologically relevant to suitable grapevine growing conditions and climatic factors that are known to contribute to premium viticulture. The mean percent contribution and permutation importance of each variable across five simulations are shown.

Table S5. Comparison of different human impact thresholds with independent estimate of remaining natural lands

	Threshold, % natural land			
Hotspot name	HFP25	HII10	HII5	Estimate
Atlantic Forest	19	1	0	8
California floristic province	***60***	***22***	***10***	***25***
Cape floristic region	***67***	***31***	***17***	***20***
Caribbean islands	11	3	2	10
Caucasus	26	1	0	27
Cerrado	58	24	14	22
Chilean winter rainfall and Valdivian forests	***63***	***30***	***24***	***30***
Coastal forests of eastern Africa	62	12	6	10
East Melanesian islands	67	8	2	30
Eastern Afromontane	43	5	2	10
Guinean Forests of west Africa	24	1	0	15
Himalaya	60	26	17	25
Horn of Africa	82	25	10	5
Indo-Burma	42	5	2	5
Irano-Anatolian	33	2	1	15
Japan	14	0	0	20
Madagascar and Indian Ocean islands	60	13	4	10
Madrean Pine-Oak Woodlands	62	15	5	20
Maputaland-Pondoland-Albany	54	18	11	24
Mediterranean Basin	***29***	***5***	***1***	***5***
Mesoamerica	28	6	2	20
Mountains of Central Asia	67	16	8	20
Mountains of Southwest China	68	20	8	8
New Caledonia	34	1	0	27
New Zealand	***65***	***37***	***25***	***22***
Philippines	18	1	0	7
Polynesia-Micronesia	56	13	4	21
Southwest Australia	74	48	34	30
Succulent Karoo	93	76	46	29
Sundaland	56	28	19	7
Tropical Andes	62	29	18	25
Tumbes-Choco-Magdalena	34	11	2	24
Wallacea	59	17	10	15
Western Ghats and Sri Lanka	26	0	0	23
Total	48	14	8	15

Values are the percentage of total hotspot area classified as natural land under each threshold. Wine-producing regions in this analysis are in boldface italics. HFP25 is a threshold based on the same dataset (1) where human footprint > 25. It differs from HII in that the raw values of the HII are stretched to produce a score from 0 to 100 for each biome. HFP was the threshold used in Murdoch et al. (2) and Underwood et al. (3), studies that assessed conservation return on investment. HII10 is the threshold used for this manuscript, whereas HII5 represents a stricter threshold for "natural" or "unaltered" lands. The three thresholds tested are arranged in order from least restrictive (i.e., more land is classified as natural) to most restrictive. As shown, our choice of threshold was the best match to an independent global assessment of remaining natural areas in biodiversity hotspots [CI Estimate; Myers et al. (4)]. HFP, human footprint.

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2. Murdoch W, et al. (2007) Maximizing return on investment in conservation. *Biol Conserv* 139(3-4).
3. Underwood EC, et al. (2008) Protecting biodiversity when money matters: Maximizing return on investment. *PLoS ONE* 3(1):e1515.
4. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* 403(6772):853–858.