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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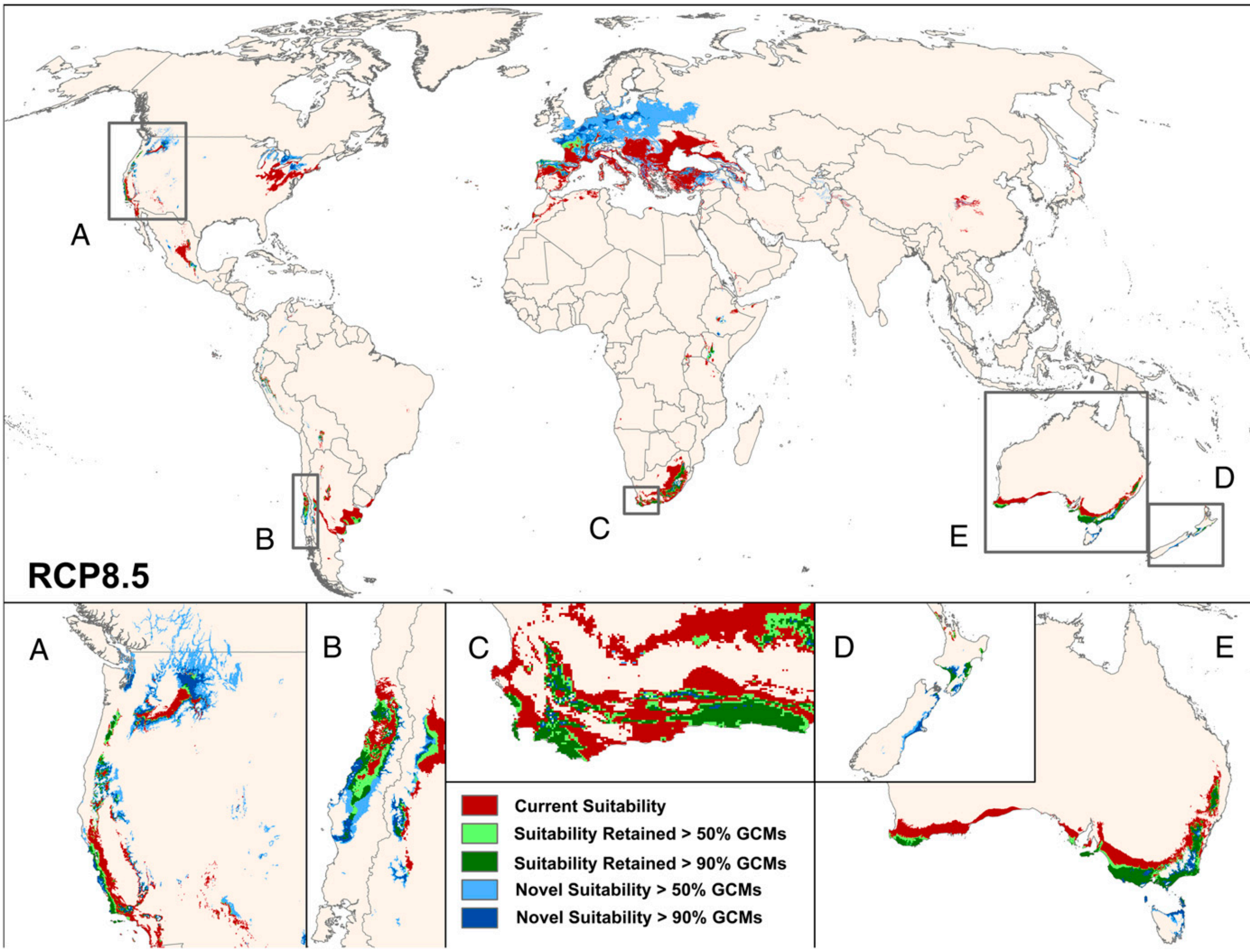

Fig. 1. Global change in viticulture suitability RCP 8.5. Change in viticulture suitability is shown between current (1961–2000) and 2050 (2041–2060) time periods, showing agreement among a 17-GCM ensemble. Areas with current suitability that decreases by midcentury are indicated in red (>50% GCM agreement). 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

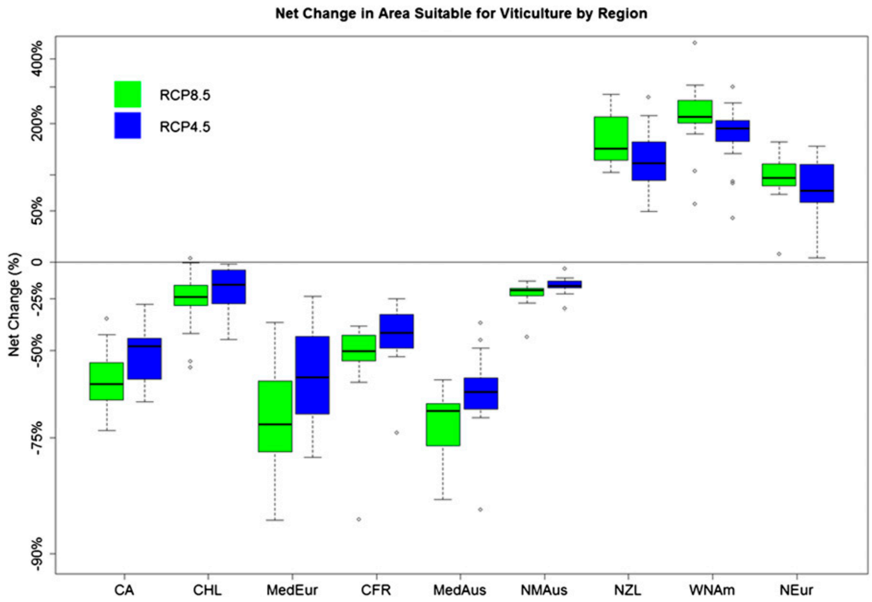

Fig. 2. Net viticulture suitability change in major wine-producing regions. Box plots show median values and quantiles of change in area suitable for viticulture projected by 17-member model ensemble for RCP 8.5 (green) and RCP 4.5 (blue). Mediterranean-climate wine-producing regions show declines, whereas 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, multi-organization 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 (38), 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

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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 2) 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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