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 has 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 declines 25%-73% in major wine producing regions by 2050 in the higher RCP 8.5 concentration pathway and 19%-62% in 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.

Climate Change | Conservation | Viticulture

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 winter) 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 non-native 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 (23-24). Vineyard water use for frost damage prevention has resulted in significant flow reduction in California streams (24). 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 (24). Potential damage to freshwater environments is generally highest where water is already scarce (25). Climate change may bring precipitation decreases to some regions, increasing the need for irrigation, which may result in impacts on freshwater ecosystems. Traditions of irrigation, limited in Europe (26) and higher in other parts of the world (e.g., California, Chile) (27) 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 due to 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; see Table S1) under two Representative Concentration Pathways (RCP). Habitat impact is assessed using an ecological footprint index, which measures the intersection of viticultural suitability with remaining natural habitat (28). The potential for impact on freshwater provisioning is assessed using the intersection of water stress (29), 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 1971-2000) and 2050 (mean of 2041-2060) with high agreement among the results obtained with17 GCMs. Suitability is projected to decline (red in Fig. 1) 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 both RCP 8.5 and RCP 4.5. Current suitability is projected to be retained (50% of GCMs – light green, 90% of GCMs – dark green) in smaller areas of current wine-producing

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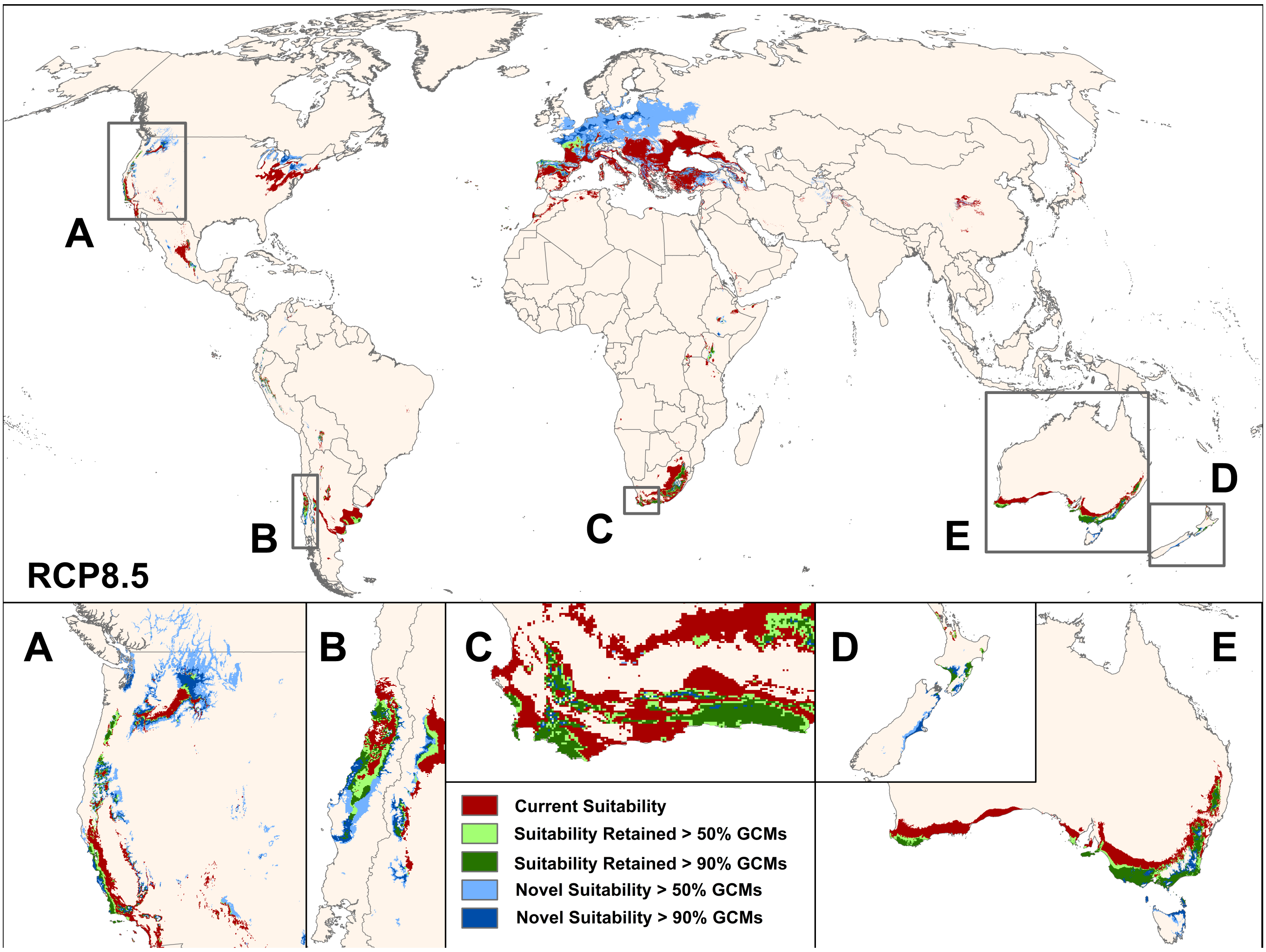

Fig. 1. Global change in viticulture suitability RCP 8.5. Change in viticulture suitability is shown between current (1971-2000) and 2050 (2041-2060) time periods, showing agreement among a 17 GCM ensemble. Areas with current suitability that declines by mid-century are indicated in red (>50% GCM agreement). Areas with current suitability that is retained are indicated in light green (>50% GCM agreement) and dark green (>90% GCM agreement), while 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 show e greater detail for major wine growing regions – (left to right) California/Western North America (A), Chile (B), the Cape of South Africa (C), New Zealand (D) and Australia (E).

regions, especially at upper elevations and in coastal areas. At higher latitudes (main map) and at elevations (insets) areas not currently suitable for viticulture are projected to become suitable in the future (50% of GCMs – light blue, 90% of GCMs – dark blue).

To understand these geographic shifts in more detail, we examine ensemble mean change and variation among ensemble members (the 17 GCMs) for 9 major wine producing regions (Fig. 2). Five of these 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 decline ranges from 25% in Chile to 73% in Mediterranean Australia under RCP 8.5 and from 19%-62% under RCP 4.5 (see Fig. 2). Non-Mediterranean Australia sees slight declines in suitable area while 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 increase in suitable area is 231% in Western North America and 99% in Northern Europe in RCP 8.5, and 189% and 84% under RCP 4.5 (see 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 (see Fig. 2). These changes in suitability for viticulture may have impacts on both 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 14% under RCP 8.5) and California (mean increase 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%

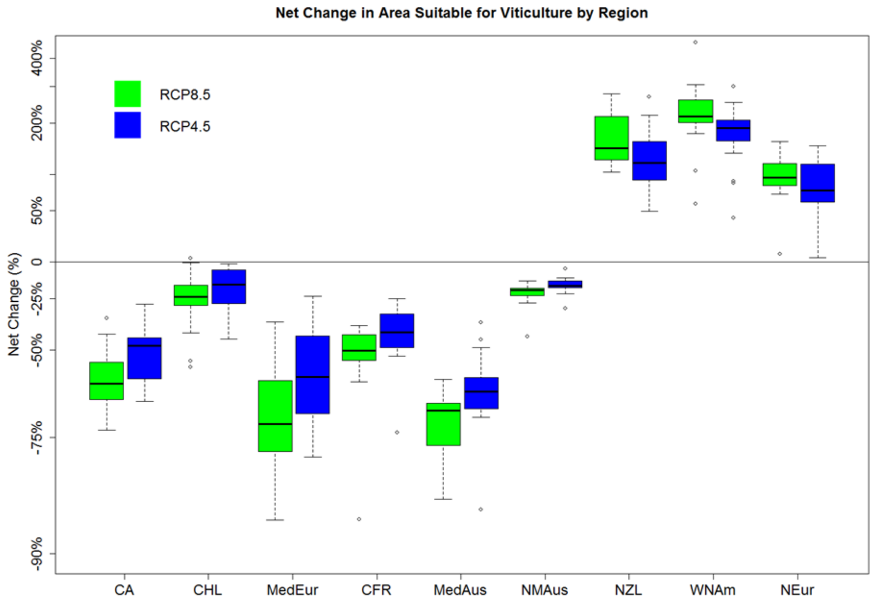

Fig. 2. Net Viticulture Suitability Change in Major Wine-producing Regions. Boxplots show median and quantiles of change in area suitable for viticulture projected by 17 member model ensemble, for RCP 8.5 (green) and RCP 4.5 (blue). Mediterranean climate wine-producing regions show declines, while New Zealand, Western North America and Northern Europe show substantial increases in suitable area (note that vertical axis is log transformed). CA=California Floristic Province, CHL=Chile, MedEur=Mediterranean climate Europe, MedAus=Mediterranean climate Australia, CFR = Cape Floristic Region (South Africa), NMAus=Non-Mediterranean climate Australia, NZL=New Zealand, WNAm=Western North America, NEur=Northern Europe. See Fig. S4 panel B for regional definitions.

Table 1.

RCP8.5	Net Change in Area Suitable for Viticulture (mean %)	Current Ecological Footprint (% area) {ha x 10^6}	Ecological Footprint Trend to 2050 (% change)	Decline in Area Currently Suitable for Viticulture (mean % loss)	Existing water stress (mean % area)	Precipitation trend to 2050 (mean % change)	Freshwater Impact Index (mean % area)
California	-60 [-42,-55,-66,-73]	29.8 {2.8}	10 [2,5,11,27]	70 [50,64,77,83]	85.9	-2.0 [-26.5 ,-10.8,4.2,16.2]	40.4 [0,2,85,85]
Chile	-25 [0,-17,-29,-55]	0.8 {0.05}	0 [-38,-25,38,50]	47 [23,35,59,81]	94.6	-15.5 [-29.3, -21.4,-9.8,-0.8]	84.1 [49,94,95,95]
Mediterranean Europe	-68 [-39,-61,-78,-86]	2.4 {1.8}	342 [125,263,392,525]	85 [54,80,96,100]	50.7	-8.4 [-20.4,-11.8,-4.1,-0.1]	42.9 [24,43, 49,50]
Cape Floristic Region	-51 [-41,-44,-54,-66]	46.0 {2.5}	14 [9,11,15,19]	55 [45,48,58,70]	44.9	-9.8 [-22.4,-10.8,-5.0,-3.1]	39.7 [27,41,44,44]
Australia (Med)	-73 [-61,-67,-76,-87]	44.0 {15.1}	-5 [-16,-8,0,6]	74 [62,69,78,88]	3.0	-10.6 [-18.5,-15.8,-4.5,11.6]	2.7 [0,3,3,3]
Australia (Non-med)	-22 [-15,-19,-23,-31]	40.9 {13.8}	2 [0,2,5,11]	46 [36,37,50,59]	34.6	-1.5 [-11.2,-6.0,2.0,10.7]	22.5 [0,13,35,35]
Northern Europe	+99 [58,83,118,149]	1.1 {2.5}	191 [-10,10,291,618]	84 [48,74,98,100]	17.2	-3.0 [-10.6,-7.1,-0.1,5.8]	17.8 [7,14,23,24]
New Zealand	+168 [104,124,216,264]	6.6 {0.1}	126 [98,103,152,174]	17 [0,10,23,33]	0	-1.2 [-8.1,-3.7,1.3,4.7]	0 [0,0,0,0]
Western North America	+231 [96,201,259,338]	44.1 {4.9}	16 [2,12,23,28]	59 [34,52,72,78]	23.7	-0.4 [-9.5,-4.9,3.5,9.0]	16.9 [0,9,30,33]

- Ecological Footprint and Freshwater Impact Index under climate change for prominent winegrowing regions RCP 8.5.
* Ensemble means are shown, with quantiles shown in brackets, in the order [5%, 25%, 75%, 95%].
† Ecological Footprint is the percentage of suitable viticulture area that intersects with natural lands as defined by Human Influence Index < 10 (53)
‡ 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 water stress index > 0.2 (26)
¶Freshwater Impact Index 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 water stress index > 0.2.
‖RCP 4.5 values are given in Table S2

RCP 8.5), followed by New Zealand (126% RCP 8.5). Western North America has the highest absolute area increase, since 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 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 viticultual suitability (an index of potential need for water for irrigation or grape cooling), projected decrease in precipitation and pre-existing high water stress within each region provides an index of the potential for freshwater conservation impacts ('Freshwater Impact Index', Table 1). The ensemble average of this index is highest in Chile at 84% under RCP 8.5, and near or in excess of 40% in California, Mediterranean Europe and the Cape of South Africa. Mediterranean Australia has a relatively low index value due to 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 due to precipitation declines. 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 precipitation decrease of 15.5% (RCP 8.5, lower quartile -21, upper quartile -10, see Table 1), 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 both 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 roughly 20% by 2050 (30). This decline, coupled with an average temperature increase of 3-4 °C in the catchment area, will affect river discharges and seasonality (31). Similarly, other major wine producing valleys (e.g. Aconcagua, Maipo, Maule) will also show a decrease in available water discharge ranging between 20 to 30% by 2050 (31, 32). 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 initiative (Y2Y), a multi-agency, multi-organization effort to provide habitat linkages for large and wide-ranging mammal species such as grizzly bear (*Ursus arcturus*), gray wolf (*Canis lupus*) and pronghorn (*Antilocapra americana)* from Yellowstone National Park north to the Yukon Territory in Canada (33). 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 (34). Future suitability for wine grapes within the Y2Y planning area is expected to increase by a factor of 19 by 2050 (Fig. S3). 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 (over 400%) within 50 km of a protected area (35). 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 (36). Maintaining the goals of Y2Y may therefore require pro-active 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 both scientific and socio-economic 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 5 regions and 2 concentration pathways that Mediterranean climate growing regions will experience a decline 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 declines 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 temperatures 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).

Frontiers for additional research are suggested by several of our results. Wine production in tropical montane areas projected as suitable for viticulture – both currently and in the future (see 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 now a major producer of 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 due to 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 on the 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, since they are moved through human action independent of contiguous habitat or natural dispersal processes. New vineyard establishment anticipating improving conditions may 'leap frog' intervening areas, while 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 (37), 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, while 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 (see Fig. 2), but subject to important regional refinements. Local soil composition and topography will strongly influence the local manifestation of the global patterns (38), making regional studies an important research focus to complement this global analysis. Calculating impacts on viticultural suitability using daily extreme temperatures may yield different results than the twenty year mean monthly climatologies employed here (11, 39, 40). Other studies that have employed extreme daily temperatures show more pronounced changes in the projected range of viticultural suitability than the results presented here (11, 39, 40). Therefore our findings may be conservative. GDD estimates based on daily values may produce slightly different estimations of suitability than the GDD summation calculated from monthly means (11, 39, 40). Lower greenhouse gas concentrations (RCP 4.5) produce lesser declines in current wine-producing regions and moderate the amount of newly suitable area (see Table 2), 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. While 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, 41). The interactions between crop suitability and conservation are not one-way, as consumer preference for environmentally-friendly production may penalize commodities having 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 (42). 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 winegrowers to maintain productivity and quality as well as to minimize freshwater withdrawals and terrestrial footprint (40). 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 (43). 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. Wine, Climate Change and Biodiversity Program in Chile) will jointly benefit the industry, consumers and conservation (44).

Investment in new varieties, giving 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 micro-misters or strategic vine orientation/trellising practices to control microclimates at the level of individual grape clusters can greatly reduce water use demands (45). Increases in water use may be limited, at least in the near term, in areas where irrigation is traditionally avoided due to tradition or regulation (e.g., parts of Europe) (26). At the same time, these policies will render adaptation to climate change more difficult. Chile and California are areas with traditions of irrigation (27) and high water impact index values, indicating that their freshwater habitats may be most at risk due to 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 both declining and 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 UNFCCC goals of maintaining sustainable development and allowing ecosystems to adapt naturally can only be achieved if adaptation includes consideration of secondary impacts of agricultural change on ecosystems and biodiversity.

Materials and Methods

Climatologies. For current (1971-2000) climate we used the WorldClim global climate dataset on a 2.5 arc minute grid (46). For future climate projections, we used GCMs from the fifth phase of the Coupled Model Intercomparison Project (CMIP5). Future global climatologies, representing monthly twenty-year normals for 2041-2060, were downscaled from the native resolution of 17 GCMs (see Table S1) 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 (47). Bias correction has been shown to be important in climate change analyses of wine grape suitability (39).

Suitability Models. The consensus suitability model 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 multi-factor distribution model – that reflect a range of wine suitability modeling techniques suggested in the literature that are implementable using standard 20-year monthly climate normals. Consensus models have been shown to be more robust than individual models in bioclimatic modeling (25) and testing shows this to be the case with our consensus suitability model (see Fig. S2 and Table S3).

For the temperature-varietal model, optimal average growing season temperatures for 21 common wine grape varieties were used as defined in Jones et al., 2005 (4). The phenological method is adapted from Hayhoe et al., 2004 (48), in which viticulture suitability is determined by biophysical response as ripening progresses. The multi-factor model was implemented using the Maxent species-distribution model, which produces a model of climatic suitability for a species at any location and/or time period based on known occurrences and present and future environmental variables (49, 50). See SI Methods for a full description of each suitability model. Minimum annual temperature > -15 °C) and annual precipitation between 255mm and 1200mm) limiting values were used to constrain individual suitability models

(3). The area of agreement across all three individual models provides the basis for the consensus model results presented here.

Ecological Footprint. We used the Human Influence Index (HII) (28) 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 score and urban/agricultural land uses to provide a continuous score of habitat integrity (28). We transformed the HII into a binary index of natural/non-natural habitats 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 (see Tables S4 and S5 for additional detail on HII threshold selection).

Water stress index (WSI) Current WSI data (Table 1) were generated by the WaterGAP2 model (29) as presented in (51). WSI is the ratio of aggregate domestic, industrial and agricultural demand to runoff in a given watershed (DIA/Q) (51). A watershed is considered to be under water stress at WSI > 0.2 (51).

Freshwater Impact Index (FII) we define as the intersection of decline in current viticulture suitability, projected mean decline in precipitation between 2000 and 2050 in our 17 GCM ensemble, and area of water stress (water stress index of > 0.2) (52). Decline 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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1. Kenny, GH and Harrison, PA (1993) The effects of climatic variability and change on grape suitability in Europe. *Journal of Wine Research* (4):163–183
2. Winkler AJ, Cook JA, Kliwer WM, Lider LA (1974) General viticulture. University of California Press, Berkeley, USA.
3. Gladstones, J (1992) Viticulture and Environment. WineTitles, Adelaide.
4. Jones GV, White MA, Cooper OR, & Storchmann K (2005) Climate change and global wine quality. *Clim. Change* 73(3):319-343.
5. Nemani RR, *et al.* (2001) Asymmetric warming over coastal California and its impact on the premium wine industry. *Climate Research* 19(1):25-34.
6. Meier N, Rutishauser T, Pfister C, Wanner H, & Luterbacher J (2007) Grape harvest dates as a proxy for Swiss April to August temperature reconstructions back to AD 1480. *Geophys. Res. Lett.* 34(20).
7. Pfister, C. (1988) Variations in the spring-summer climate of central Europe from the High MiddleAges to 1850, in *Long and Short Term Variability of Climate*, H. Wanner, U. Siegenthaler (eds.) Springer-Verlag, Berlin, 57–82.
8. White MA, Diffenbaugh NS, Jones GV, Pal JS, & Giorgi F (2006) Extreme heat reduces and shifts United States premium wine production in the 21st century. *PNAS* 103(30):11217-11222.
9. Ladurie, ELR (1967) Histoire du climat depuis l'an mil [History of climate since the year one thousand]. Paris, 1967. 379p.
10. Vaudour, E (2002) The quality of grapes and wine in relation to geography: Notions of terroir at various scales: *Journal of Wine Research*, (13):117-141.
11. White, MA, Whalen, P & Jones, GV (2009) Land and wine. *Nat. Geosci.* (2):82-84
12. Cowling RM, Rundel PW, Lamont BB, Arroyo MK, & Arianoutsou M (1996) Plant diversity in Mediterranean-climate regions. *Trends Ecol. Evol.* 11(9):362-366.
13. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, & Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* 403(6772):853-858.
14. Underwood EC, Viers JH, Klausmeyer KR, Cox RL, & Shaw MR (2009) Threats and biodiversity in the mediterranean biome. *Diversity and Distributions* 15(2):188-197.
15. Turner WR, *et al.* (2010) Climate change: helping nature survive the human response. *Conservation Letters* 3(5):304-312.
16. Coulouma G, Boizard H, Trotoux G, Lagacherie P, & Richard G (2006) Effect of deep tillage for vineyard establishment on soil structure: A case study in Southern France. *Soil Tillage Res.* 88(1-2):132-143.
17. Coll P, Le Cadre E, Blanchart E, Hinsinger P, & Villenave C (2011) Organic viticulture and soil quality: A long-term study in Southern France. *Applied Soil Ecology* 50:37-44.
18. Hilty JA, Brooks C, Heaton E, & Merenlender AM (2006) Forecasting the effect of land-use change on native and non-native mammalian predator distributions. *Biodiversity and Conservation* 15(9):2853-2871.
19. Hilty JA & Merenlender AM (2004) Use of riparian corridors and vineyards by mammalian predators in northern California. *Conserv. Biol.* 18(1):126-135.
20. Altieri MA & Nicholls CI (2002) The simplification of traditional vineyard based agroforests in northwestern Portugal: some ecological implications. *Agroforestry Systems* 56(3):185-191.
21. Fairbanks DHK, Hughes CJ, & Turpie JK (2004) Potential impact of viticulture expansion on habitat types in the Cape Floristic Region, South Africa. *Biodiversity and Conservation* 13(6):1075-1100.
22. Lohse KA, Newburn DA, Opperman JJ, & Merenlender AM (2008) Forecasting relative impacts of land use on anadromous fish habitat to guide conservation planning. *Ecol. Appl.* 18(2):467-482.
23. Lawrence JE, Deitch MJ, & Resh VH (2011) Effects of vineyard coverage and extent on benthic macroinvertebrates in streams of Northern California. *International Journal of Limnology* 47(4):347-354.
24. Deitch MJ, Kondolf GM, & Merenlender AM (2009) Hydrologic impacts of small-scale instream diversions for frost and heat protection in the California wine country. *River Res. Appl.* 25(2):118-134.
25. Vorosmarty CJ, *et al.* (2010) Global threats to human water security and river biodiversity *Nature* 468(7321):334-334.
26. Robinson J (1996) Oxford Companion to Wine. Oxford University Press, Oxford UK.
27. Orang MN, Matyac JS, & Snyder RL (2008) Survey of irrigation methods in California in 2001. *Journal of Irrigation and Drainage Engineering-Asce* 134(1):96-100.
28. Sanderson EW, *et al.* (2002) The human footprint and the last of the wild. *Bioscience* 52(10):891-904.
29. Alcamo J, *et al.* (2003) Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrol. Sci. J.* 48(3):317-337.
30. Fuenzalida H, Aceituno P, Falvey M, Garreaud R, Rojas M, Sanchez R (2007) Study on Climate Variability for Chile during the 21st century. Technical Report prepared for the National Environmental Committee, Chile. Spanish.
31. CEPAL (2009) La Economía del Cambio Climático en Chile, Síntesis. [The Economics of Climate Change in Chile – Synthesis] CEPAL, Chile. Spanish.
32. MMA (2011) Segunda Comunicación Nacional de Chile Ante la Convención Marco de las Naciones Unidas Sobre Cambio Climático[Second National Communication of Chile to the UN Framework Convention on Climate Change]. Ministerio del Medio Ambiente [Ministry of Environment], Chile. Spanish
33. Graumlich, L and Francis WL (Eds.) (2010) Moving Toward Climate Change Adaptation: The Promise of the Yellowstone to Yukon Conservation Initiative for addressing the Region's Vulnerabilities. Yellowstone to Yukon Conservation Initiative. Canmore, AB.
34. British Columbia Wine Institute. (2011) 2011 B.C. Winegrape acreage report. Kelowna, BC Canada.
35. Radeloff VC, *et al.* (2010) Housing growth in and near United States protected areas limits their conservation value. *PNAS* 107(2):940-945.
36. Flaherty, DL, Christensen LP, and Lanini WT, eds. (1992) Grape pest management, 2nd ed. Oakland: University of California Division of Agriculture and Natural Resources, Publication 3343.
37. Davis, M. B. and R. G. Shaw (2001). "Range shifts and adaptive responses to Quaternary climate change." *Science* **292**(5517): 673-679.
38. Bramley, RGV & Hamilton, RP (2004) Understanding variability in winegrape production systems 1. Within vineyard variation in yield over several vintages. *Aust. J. Grape Wine Res.* (10):32-45.
39. 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* DOI:10.1007s00382-012-1377-1.
40. Diffenbaugh NS, White MA, Jones GV, & Ashfaq M (2011) Climate adaptation wedges: a case study of premium wine in the western United States. *Environmental Research Letters* 6(2).
41. Lobell DB, Schlenker W, & Costa-Roberts J (2011) Climate Trends and Global Crop Production Since 1980. *Science* 333(6042):616-620.
42. Wetzel FT, Kissling DW, Beissmann H & Penn DJ (2012) Future climate change driven sea-level rise: secondary consequences from human displacement for island biodiversity. *Global Change Biology* 18: 2707–2719.
43. Biodiversity & Wine Initiative (2012) www.varietyisinournature.com.
44. El Programa Vino, Cambio Climático y Biodiversidad [Wine, Climate Change and Biodiversity Program] In Spanish.
45. Greenspan, M (2009) Investigating low-volume approaches to vineyard cooling. *Wine Business Monthly*. January 15, 2009.
46. Hijmans RJ, Cameron SE, Parra JL, Jones PG, & Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* 25(15):1965-1978.
47. Leemans R & Solomon AM (1993) Modeling the potential change in yield and distribution of the earth's crops under a warmed climate. Climate Research 3:79-96.
48. Hayhoe K, *et al.* (2004) Emissions pathways, climate change, and impacts on California. *PNAS* 101(34):12422-12427.
49. Phillips SJ, Anderson RP, & Schapire RE (2006) Maximum entropy modeling of species geographic distributions. *Ecol. Modell.* 190(3-4):231-259.
50. Graça, AR (2009) Wine Regions of the World - Version 1.3.2.
51. Pfister S, Koehler A, & Hellweg S (2009) Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ. Sci. Technol.* 43(11):4098-4104.
52. Vorosmarty CJ, Green P, Salisbury J, & Lammers RB (2000) Global water resources: Vulnerability from climate change and population growth. *Science* 289(5477):284-288.