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Impacts of global warming on southern California's winegrape climate suitability

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Abstract

Southern California has seen a resurgence of winegrowing regions in the past few decades, however the future of winegrape climatic suitability in the area has not been exhaustively explored. This study evaluated the future climate suitability for the cultivation of winegrape and potential global warming impacts on southern California's winegrowing regions through a series of high-resolution surface air temperature and precipitation projections obtained with the WRF-SSIB regional climate model. Results reveal that by mid-21st-century the surface air temperature will increase by approximately 1.2 °C, while average precipitation will decrease by as much as 11% in the southern winegrowing areas under the Intergovernmental Panel on Climate Change high greenhouse-gas emissions scenario. Evaluation of bioclimatic suitability indices indicate increases in heat accumulation for all major winegrowing areas; including an increase of about 10% in growing-degree day, while morning low temperatures in September may experience increases of approximately 11% in the future, thus impacting negatively the ripening stage of grapevines and leading to changes in wine composition and quality. Additionally, the extent of areas classified under the cool to warm climate suitability categories could decrease by nearly 42% in the study area by 2050. Conditions in southern California are already warm and dry for viticulture and continuing heat accumulation increase, along with rainfall reduction, could potentially place additional stress to winegrape crop in the area, including advanced phenological timing and moisture deficit stress that could lead to decreases in yield. The projected decline in viticulture suitability highlights the need for adaptive capacity within this sector to mitigate the impacts of global warming. Possible mitigating strategies include planting hotter climate grape varieties, moving vineyards to regions that are more suitable in the future, and adopting dry-farming techniques.

Keywords: Global warming; Winegrape suitability; Regional climate modeling; Bioclimatic indices; Dynamical downscaling

1. Introduction

Winegrape is a valuable perennial crop in southern California and describes the types of grapes grown from grapevines (*Vitis vinifera*) used in the production of wine. Grapevines were first introduced to the area in 1769 and their production in the region is growing economically and gaining favorable attention. San Diego county's 2018 gross sales at wineries increased 57.1% over 2017 sales (SDCVA, 2019) and a similar report for Santa Barbara county stated that the industry supported 9158 full-time equivalent jobs and had an economic impact of 1.7 billion USD (SBCVA, 2013). Although this crop is economically valuable to this region, it is limited in its geographic extent (30°–50°N), is extremely sensitive to short-term variability and long-term changes in climate (Jones and Webb, 2010), and is perhaps one of the most sensitive crops to climatic change, compared to other regional crops such as walnut, orange, avocado, and corn (Bindi et al., 1996; Lobell et al., 2006; Cahill et al., 2007;

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Burke and Emerick, 2016). Due to recent trends in temperature, concern has grown over the impact that long-term climatic change might have on agriculture (Pathak et al., 2018; IPCC, 2019) as climate is a main determinant in productivity (Adams et al., 1998). To understand future climate and conditions that could impact human and natural systems, temperature suitability of winegrape production is commonly used as a climate impacts indicator (Diffenbaugh and Scherer, 2012). In addition, studies have looked at the impact of global warming on the classification of winegrowing regions and have found significant changes in suitable regions for mid- and end-21st-century scenarios. White et al. (2006) concluded that premium winegrape production in the USA could decline by 81% by the end of the 21st century. Studies also suggest that warmer and prolonged growing seasons will shift production towards warmer-climate varieties and perhaps lower quality wines (Cahill et al., 2007; Ruml et al., 2012). Additionally, cooler regions will become more suitable to viticulture, but production may be limited due to non-climatic influences (Cahill et al., 2007).

Wine growing regions are classified based on the climatic potential for winegrape production determined by bioclimatic indices. There are typically 5−6 classes that range from ‘cool’ to ‘very hot’ regions. There are several indices including the multicriteria climatic classification system (Tonietto and Carbonneau, 2004), growing degree day calculation (Jones et al., 2010), biologically effective degree days calculation (Gladstones, 1992), and 15 climatically important parameters involving heat accumulation, frost-related characteristics, and precipitation characteristics (Jones and Goodrich, 2008). Global and regional studies, using subsets of the above indices, have assessed past, present, and future changes in winegrowing regions due to climate change and concluded that while some mid-latitude continental-climate areas, such as central Europe, may benefit from the increasing heat accumulation associated from global warming, coastal and warmer-climate areas, such as central northern California, will potentially experience a reduction in suitable for winegrowing (Jones et al., 2010; Neumann and Matzarakis, 2011; Ruml et al., 2012; Hannah et al., 2013; Teslic et al., 2018).

Studies show a progressive warming trend in indices and geographic change in optimal regions for winegrape production. Regions that were once too cool or moist for cultivation of winegrape will become more suitable towards mid- and late-21st-century (Hannah et al., 2013). Areas that are currently producing fruit in the warmest regions might become too warm for high-quality winegrape production (White et al., 2006). Suitable growing regions are transitioning to higher latitudes and greater elevations, as these areas are now becoming warmer and less moist. Studies focused on the suitability of California, show that from 1951 to 1997 climatic changes might have benefited the premium wine industry due to the increase in sea surface temperature, rise in atmospheric vapor, and modest trend in annual temperature rise (Nemani et al., 2001).

While past warming trends might have proven beneficial, future-climate studies for California identify three potential changes: first, a shift from marginal to impaired conditions for central valley grape-growing regions (Cahill et al., 2007; Diffenbaugh et al., 2011), second, an increase in growing season temperature of 3.0 °C by 2049 for southern California compared to a historical period (Jones, 2005), and third, an increase in growing season and ripening season hot days of 3−8 weeks by the end of the 21st century for southwestern USA, potentially eliminating premium winegrape production in this region (White et al., 2006). Although clear trends in winegrowing responses to increased global temperatures have been established, these studies focused on global or large-scale analysis rather than a regional or localized approach.

Climate change studies based on the Intergovernmental Panel on Climate Change (IPCC) fifth Coupled Model Intercomparison Project (CMIP5) indicate that temperatures in the region are predicted to increase and precipitation amounts are expected to be more variable during the 21st century (Maloney et al., 2014; Pierce et al., 2018). The spatial resolution of the climate model used in CMIP5, however, are generally too coarse to capture the regional atmospheric processes observed in complex-terrain areas such as southern California, and downscaling techniques are often employed to improve the regional representation of climate simulations (Leung et al., 2006; De Sales and Xue, 2013).

This study aims at improving the current understanding of the effects of global warming on the region's viticulture by generating accurate regional-scale information about the crop's climatic suitability that can assist local growers in the development of strategies to alleviate the negative impacts of a warmer climate. We examined changes to mid-21st century southern California's winegrape climatic suitability resulting from global warming following the IPCC's high greenhouse-gas emission scenario by comparing high-resolution historic and future climate projections generated through a series of physically-based regional climate model simulations. The analysis relies primarily on changes to bioclimatic suitability indices. Other influencing environmental factors such as the direct effects of elevated levels of atmospheric carbon dioxide are not considered.

2. Data and methods

2.1. Study area

Southern California is characterized by a mediterranean, semi-arid, and desert climate with warmer summers and cooler winters. Coastal regions are enclosed by two mountain ranges: the Transverse Range which extends eastward from Point Arguello, Santa Barbara and the Peninsular Range stretching northward from the Mexican border. This mountain boundary creates a triangular coastal sector located along 200 miles of Pacific Ocean coastline. This area is invaded by sea air which maintains moderately stable temperatures and increased moisture levels (Bailey, 1966). Winegrowers take advantage of the resultant meso- and micro-climates of southern California.

To distinguish differences in southern and northern regions and to evaluate potential variations in climate structures for viticultural purposes, the model domain is divided into four winegrape growing regions (North, North Central, South Central, and South) based upon established American Viticultural Areas (AVAs) (CFR, 2008). AVAs attribute characteristics of winegrape to the specific geographic location where it was grown (Fig. 1).

2.2. Modeling system

Climate simulations are carried out using the Weather Research and Forecasting (WRF) regional climate model (Skamarock et al., 2008; Zhang et al., 2012a, 2012b; Powers et al., 2017; De Sales et al., 2019). The WRF is an advanced and fully compressible regional climate model built upon a system with terrain-following hydrostatic vertical and staggered Arakawa C-grid-type horizontal coordinates (Skamarock et al., 2008). The Simplified Simple Biosphere (SSiB) land surface model is used to calculate land surface–atmosphere interactions (De Sales et al., 2016; Bagley et al., 2014). SSiB is a biophysical model that calculates photosynthesis-controlled surface processes, while conserving energy, water and momentum at the atmosphere-land surface interface (Xue et al., 1991). The atmosphere-biosphere coupled regional climate model formed by these two models will be referred to as WRF-SSiB henceforth. More information about the WRF-SSIB physics options is described in De Sales and Rother (2020).

The domain for this study has a 10-km horizontal resolution, 38 atmospheric and three soil levels, and is bounded by 113°–121°W and 31°–37°N. This domain contains all winegrape study AVAs. Two sets of experiments were carried out. The first consists of 30-year historical simulation from 1983 to 2012, which represents the benchmark or control case, the second is a 30-year warming scenario experiment from 2021 to 2050 in which greenhouse gas concentrations are increased throughout the run. Each set of experiments was repeated three times, beginning from different starting days to reduce uncertainties associated with the initial conditions.

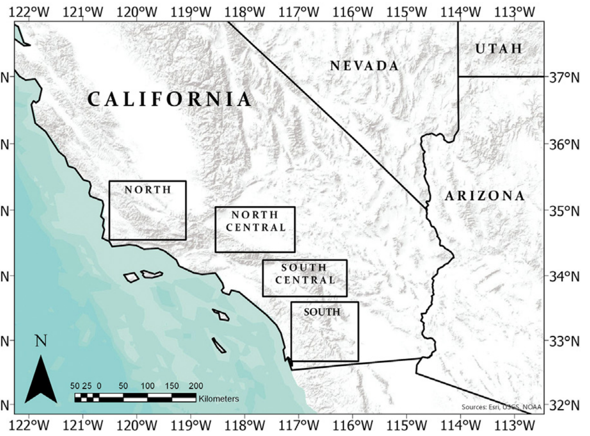

Fig. 1. Study area map with marked winegrape growing regions based on American Viticultural Areas (AVAs).

A total of 180-year climate simulations were carried out. These simulations are non-trivial, computationally intense, and constitute a proof-of-concept approach for estimating potential changes to the climatic suitability associated with global warming in southern California using the WRF-SSiB model. This model has not been extensively utilized in climate projection studies. In addition, regional climate model dynamical downscaling offers a more realistic representation of the land surface heterogeneity than GCM and can simulate regional-scale physical processes, such as topographically-induced wind circulation and precipitation patterns, which are often beyond GCM's capabilities and statistical downscaling methods (Gutmann et al., 2012; Xue et al., 2014; Chen et al., 2019). This method of climate data downscaling has been applied extensively to the USA (Xue et al., 2001, 2012; Chan and Misra, 2011; De Sales and Xue, 2013).

2.3. Forcing and validation data

Initial and boundary condition information for the WRF-SSiB simulations are extracted from the World Climate Research Programme CMIP5 (Taylor et al., 2012) MIROC5 atmosphere-ocean general circulation model (Watanabe et al., 2010). A detailed evaluation of several CMIP5 participating models' historical (1979–2005) simulations of continental and regional climatology for North America concluded that MIROC5 performed reasonably well across all seasons and regions (Sheffield et al., 2013a). MIROC5 performed better than most models particularly in simulating air temperature in western North America, with winter and summer mean near-surface air temperature biases of 0.27 °C and 2.79 °C, respectively. MIROC5 historical simulations captured the moisture flux divergence patterns over west North America associated with the North Pacific anticyclone particularly well; this is often responsible for southern California's dry and warm summers. The model also reproduces reasonably well the temperature anomalies observed in the USA associated with ENSO (Sheffield et al., 2013b).

To highlight the effects of global warming, the study focuses on the IPCC CMIP5's Representative Concentration Pathway (RCP8.5) high greenhouse-gas emissions scenario, which combines assumptions of high population and limited rates of technological change and energy intensity improvements, leading to long-term greenhouse gas emissions in absence of climate change policies (Riahi et al., 2011). Current trends in annual greenhouse gas global emissions are consistent with the RCP8.5 scenario (Peters et al., 2013). The examination of MIROC5 results under RCP8.5 conditions shows that the model projects warmer temperatures (+2.2 °C) and reduced precipitation (−10%) for California on average for 2077–2099 compared to the 1981–2010 baseline (Thorne et al., 2016).

WRF-SSiB historical simulation results are validated with the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset, which represents an advanced method to calculating gridded climate data for mountainous regions, especially for the coastal regions of the western USA (Daly et al., 2008; Strachan and Daly, 2017).

2.4. Bias correction

The Empirical Quantile Mapping (EQM) method is employed to bias correct simulations (Gutjahr and Heinemann, 2013; Luo et al., 2018). EQM, attempts to map a modeled variable using a transform of the cumulative distribution function (CDF) of the variable such that its new distribution equals the distribution of the observed variable. An underlying assumption of most quantile mapping methods is that the climate distribution does not change much over time, that is, it is stationary in the variance and skew of the distribution, and only the mean is variable. This assumption is not necessarily true in future-climate projections, especially under global warming scenarios. To overcome this problem, we used an EQM-based correction method that incorporates information from the CDF of the future-climate projections instead of assuming the historic model distribution applies to the future period (Li et al., 2010).

2.5. Multicriteria climatic classification system and indices

Winegrape crop requires specific climatic conditions to not only grow but thrive. During the winter, winegrapes require low frost damage with rainy days; during the growing season (April through October), they require ample soil moisture and sunshine with temperatures above 10 °C and low temperature variability (Jones and Davis, 2000). Specific condition variables can be categorized into growing season variables (average temperature, minimum temperature, maximum temperature), ripening period variables (average temperatures, number of days below freezing during fall and spring, date of last spring and first fall frost), and precipitation variables (precipitation during the winter, growing season, bloom period, and ripening period) (Jones and Goodrich, 2008).

Although many variables are pertinent to determine the climate structure for wine growing areas, this study focuses on a subset of the multicriteria climatic classification (MCC) system, including the heliothermal index (HI) and the cool night index (CI) developed by Tonietto and Carbonneau (2004), growing degree day (GDD) (Winkler et al., 1974; Jones et al., 2009), and growing season average temperature (GST).

These indices rely primarily on temperature, as growing season temperature is essential to vineyard yields (Sanchez and Dokoozlian, 2005). Elevated temperatures promote accumulation of grape sugars and the breakdown of organic acids leading to the grape maturing, but if temperatures become too warm, the quality of the winegrape may be negatively impacted (Haselgrove et al., 2000). There are many other factors in the complete growth cycle of the grapevine to consider. These factors include, but are not limited to, UV-B light, fire and smoke exposure, irrigation and salinity, pests,

Table 1
Climate suitability indices calculated to classify winegrowing regions.

Variable	Equation	Class intervals	
Heliothermal index (HI) (°C)	$HI = \sum_{\text{April 1}}^{\text{Sept 30}} \left(\frac{(T - T_b) + (T_{max} - T_b)}{2}\right) \times d$	Very cool	≤1500 °C
	T : mean daily air temperature	Cool	1500–1800 °C
	T_{max} : maximum daily air temperature	Temperate	1800–2100 °C
	T_b : base temperature (10 °C)	Warm temperate	2100–2400 °C
	d : length of day coefficient	Warm	2400–3000 °C
		Very warm	>3000 °C
Cool night index (CI) (°C)	$CI = \left(\frac{1}{N}\right) \sum_{\text{Sept 1}}^{\text{Sept 30}} T_{min}$	Very cool nights	≤12 °C
	T_{min} : minimum daily air temperature	Cool nights	12–14 °C
	N : number of days in the month	Temperate nights	14–18 °C
		Warm nights	>18°C
Growing degree day (GDD) (°C)[a,b]	$GDD = \sum_{\text{April 1}}^{\text{Oct 31}} [(T_{max} + T_{min})/2] - 10$	Too cool	<1111 °C
		Region I	1111–1389 °C
		Region II	1389–1667 °C
		Region III	1667–1944 °C
		Region IV	1944–2222 °C
		Region V	2222–2500 °C
		Region VI	2500–2778 °C
		Too hot	>2778 °C
Growing season temperature (GST) (°C)[a]	$GST = 1/n \sum_{\text{April 1}}^{\text{Oct 31}} (T_{max} + T_{min})/2$	Too cool	<13°C
		Cool	13–15°C
		Intermediate	15–17°C
		Warm	17–19°C
		Hot	19–21°C
		Very hot	21–24°C
		Too hot	>24°C

Notes: [a] Lower and upper bounds placed on GDD and GST according to Jones et al. (2009). [b] GDD regions represent distinct categories of heat accumulation.

disease, diurnal temperature range, proximity to a body of water, soil type, and solar reflectivity or albedo (Gladstones, 1992; Mira de Orduña, 2010). However, we focus on temperature as the main variable of analysis as it allows for the identification of climate structures pertinent to viticulture practice in southern California (Tonietto and Carbonneau, 2004).

Indices as HI, CI, GDD, and GST (Table 1) are used to classify wine regions based on climate classifications and winegrape suitability. HI measures the level of heliothermal potential and captures maximum temperatures, unlike most indices that rely on average temperature summations. HI also provides qualitative information on the sugar potential of grape varieties (Tonietto and Carbonneau, 2004). CI measures night coolness during the month when ripening occurs beyond the traditional ripening stage and provides information on the secondary metabolites in grapes which impact wine color and aromas (Tonietto and Carbonneau, 2004). GDD is very similar to HI as it calculates thermal potential during the growing season; but GDD does not consider maximum temperature.

GST calculates the average growing season temperature and broadly correlates to the maturity potential for winegrape varieties (Jones et al., 2010). Additionally, these indices have been used in many winegrowing regions analyses (Antonio et al., 2005; Jones and Goodrich, 2008; Jones et al., 2010; Neumann and Matzarakis, 2011; Ruml et al., 2012; Moriondo et al., 2013). This study will emulate these methods for southern California, a region which has not been as thoroughly studied compared to northern California winegrowing regions.

It is important to note that adjustments have not been made to the index summation time periods for HI or CI (although these indices include one less month than standard GDD or GST calculations). This was done to compare results with existing literature. Also, it was found in an earlier study that adjusting the period of indices to account for October resulted in highly correlated ($r > 0.95$) results to the original calculations (Jones et al., 2010).

3. Results

3.1. Regional analysis

Historical and future modeled average monthly temperature and precipitation spatial patterns of WRF-SSiB are depicted in Fig. 2. Projections show decreased precipitation over an eastward transect and warmer temperatures over Los Angeles (LA) county and San Diego (SD) county, compared to Santa Barbara (SB) county. Precipitation reduces by a maximum of 20 mm per month while extremely dry conditions (1−10 mm per month) dominate the southeastern desert by 2050 under the RCP8.5 scenario (Fig. 2a and b). Projected temperatures for coastal, mountain, and desert regions increase up to 2 °C (Fig. 2c and d).

Results of WRF-SSiB performance show that although the regional climate model performed well overall, the model bias correction was effective, and the corrected results are closer to observational data (Fig. 3). In general, WRF-SSiB tends to underestimate winter temperatures and overestimate summer

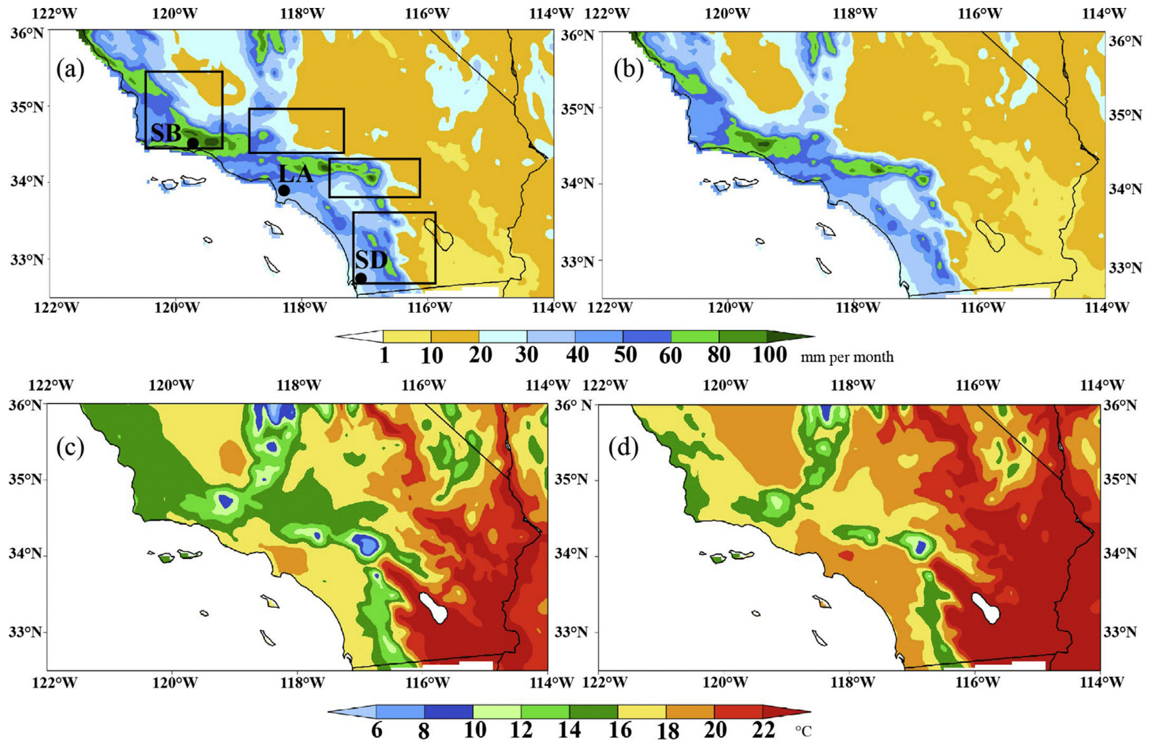

Fig. 2. Historical (a, c) (1983−2012) and future (b, d) (2021−2050) modeled spatial variability of precipitation (a, b) and temperature (c, d) under RCP8.5 (Bounding boxes in (a) indicate the winegrape growing regions. San Diego (SD) county, Los Angeles (LA) county, and Santa Barbara (SB) county marked for reference).

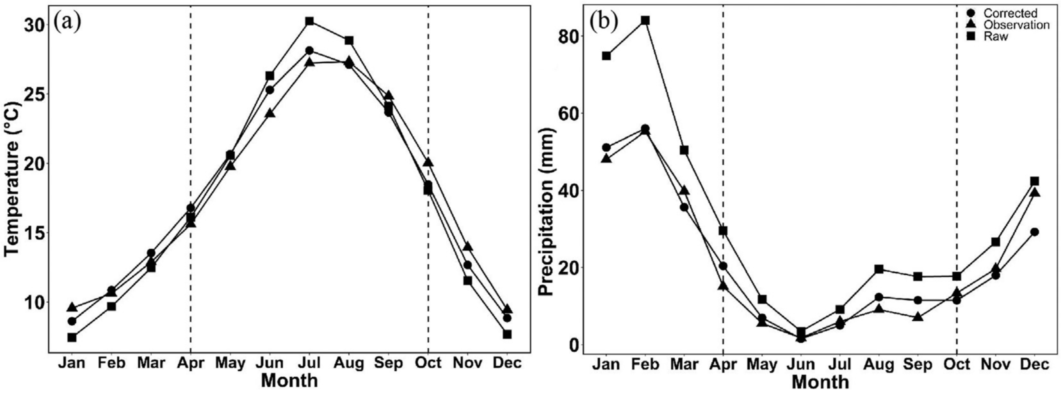

Fig. 3. Bias-corrected results for monthly temperature (a) and precipitation (b) for historical time period (1983−2012).

temperatures (Fig. 3a). Although the pattern of monthly precipitation is captured by WRF-SSiB, the model tends to overestimate the amounts, even in the growing season (Fig. 3b). In the following figures and graphs, the corrected values are used for analysis. Results show that correction is necessary to reduce overestimation of temperature and precipitation during the growing season for winegrape between April and October.

Climographs for the winegrowing regions (Fig. 4) show patterns projected for each region for historical and future conditions based on the RCP8.5 warming scenario. South, South Central, and North Central regions display statistically significant decadal decreases in modeled precipitation of 10%, 10%, and 12% by 2050, respectively. These results indicate growing regions could become more prone to experience moisture deficit stress resulting in changes to quality,

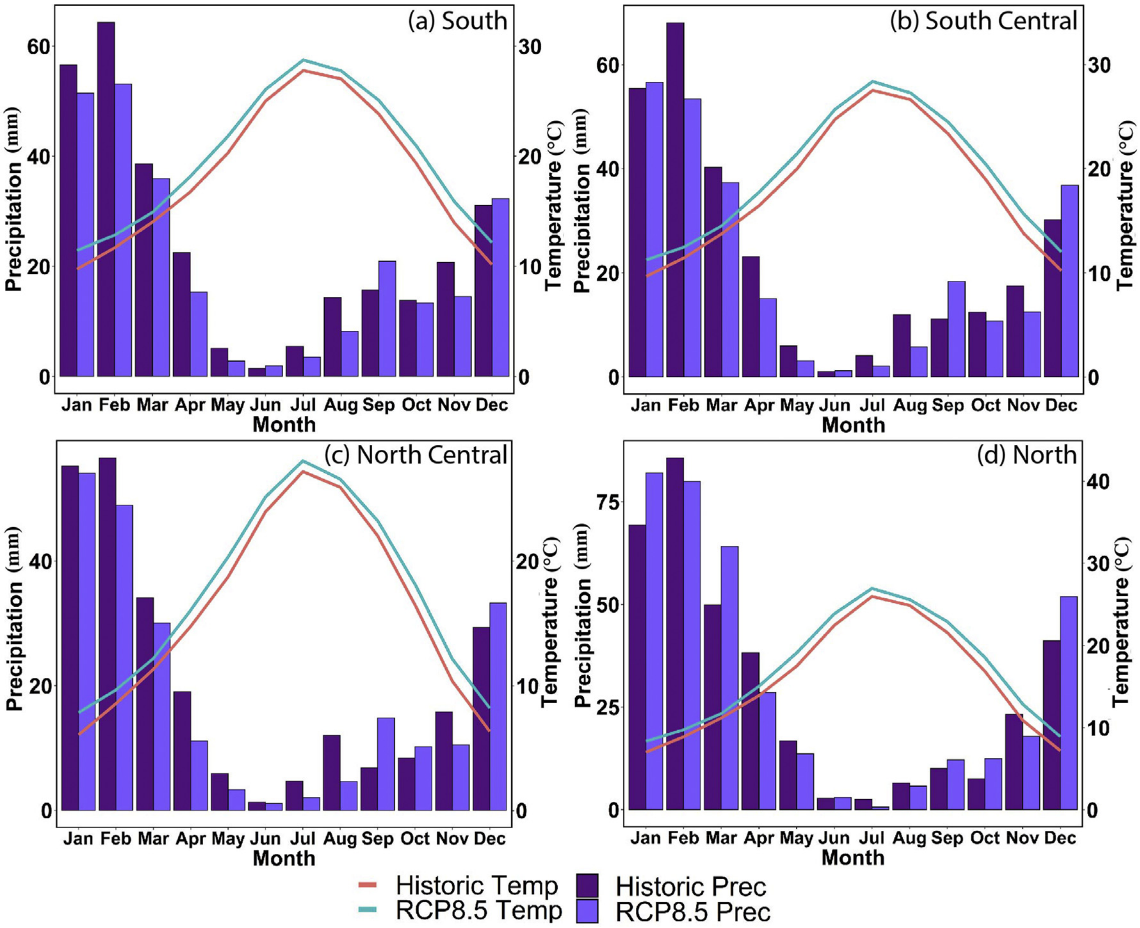

Fig. 4. Annual climographs for each winegrape growing region for historical (1983−2012) and future (2021−2050) time periods under RCP8.5 warming scenario.

Table 2
Growing season mean, maximum (Max), and minimum (Min) temperatures and corresponding decadal trends between 1983–2012 and 2021–2050 (All trends are significant at 90% confidence level ($p \leq 0.1$)).

Region	Mean temperature		Max temperature		Min temperature	
	Average (°C)	Decadal trend (°C per decade)	Max (°C)	Decadal trend (°C per decade)	Min (°C)	Decadal trend (°C per decade)
South	24.1 ± 0.7	0.50	33.0 ± 0.7	0.51	15.3 ± 0.7	0.50
South Central	23.6 ± 0.7	0.50	32.3 ± 0.7	0.51	15.1 ± 0.7	0.49
North Central	22.5 ± 0.8	0.57	31.5 ± 0.8	0.57	13.6 ± 0.8	0.61
North	21.7 ± 0.9	0.61	30.1 ± 1.0	0.68	12.3 ± 0.7	0.55

appearance, flavor, taste and aroma of the wine grape (Bonfante et al., 2017).

Annual temperature amplitude for regions South, South Central and North is approximately 17.8 °C), while the North Central region displays a much larger temperature range of nearly 21.0 °C (Fig. 4c). Regardless of geographic location, all regions experience warming trends over the next decades under the RCP8.5 scenario (Table 2). While mean temperatures are important to consider, minimum temperatures are a relevant variable as they contribute to understanding grape quality (Tonietto and Carbonneau, 2004) while maximum temperatures can have negative impacts on the grapevine, potentially leading to large percentage decreases in harvest yield (Sottile, 2017). North Central displays the largest trend in minimum growing season temperature with a decadal trend of 0.61 °C per decade while growing season maximum temperature for all regions could increase approximately 1.7 °C from 2021 to 2050. Average trend in mean temperature is 0.55 °C per decade with an increase in mean temperature over all regions of about 1.2 °C, compared to historical average.

3.2. Winegrape climatic suitability

Historical spatial suitability of climate indices is shown in Fig. 5. Areas of white indicate areas which are either too cool or too hot, based on index classes in Table 1. If regions are too cool or too hot, winegrape crop will either not produce quality fruit or will not bud properly. Cooler regions often produce higher quality wines and are situated on the Santa Barbara coastline and mountainous regions. Mid-level to warm regions typically produce good to fair quality wines and are primarily found between the coast and mountain regions and east of the mountains above 34°N.

CI (Fig. 5a) represents a large region of suitability due to the moderate climate of southern California and fall in the cool and temperate night class ranges. South displays the largest range of nighttime temperatures while North contains mainly ‘cool nights’, especially in the lower portion of its domain. Consideration of maximum daytime temperatures for HI limit regions of suitability especially for North Central region (Fig. 5d). Locations east of mountain ranges are unsuitable while the remaining suitable area falls within the warmest category for HI, except for higher latitudes. GST and GDD (Fig. 5b and c) show patterns of suitability with the most suitable land located along the coast and in mountainous areas east of SD and LA, and north of SB.

Projected suitability maps based on mid-21st-century warming scenario indicate the regions situated near and in mountainous terrain, which were once too cool for production, are now becoming suitable (Fig. 6) while inland areas between 33° N and 34° N are becoming too hot for quality wine production (Fig. 6b and c). CI continues to show the largest range of suitability (Fig. 6a) with most regions ranging between cool and temperate nights, which is ideal for winegrape development. HI constricts suitable regions to the mountains and very close to the coastline (Fig. 6d). Perhaps the only regions with an optimal range for HI suitability is South Central and North, but most regions exhibit the warmest structure when maximum temperatures are considered. GST places all regions in the warmest range of suitability for optimal winegrape growth. Although warm temperatures are required during the growing season, very warm temperatures can harm the crop, leading to reduced quality (Keller, 2010).

Based on these projections, the extent of suitable land in the winegrowing regions will shrink over the next decades with large areas becoming unsuitable for quality production. Very warm conditions can have negative effects on the vineyard and winegrape quality. For example, extended periods of elevated temperatures can damage vineyards, impact quality, lower yields, and speed up harvest which could lead to a greater need for irrigation (Sottile, 2017; CWI, 2018).

3.3. Change in bioclimatic indices

Change in average values of bioclimatic indices show warming patterns over the mountain ranges and for southern California while more moderate changes are experienced near the northern coastline (Fig. 7). Nighttime temperatures will warm up to 3 °C for the southern mountain and desert regions (Fig. 7a) and growing season average temperatures warm by more than 1–2 °C for most of southern California (Fig. 7b).

Accumulated GDD and the HI show similar patterns in spatial change with more moderate changes experienced very close to the coast and higher latitudes (Fig. 7c and d). Spatial changes in all indices show that changes by mid-21st-century compared to the historical baseline could impact the production process and quality for winegrape crop. Based on the RCP8.5 simulation results, indices for all regions show

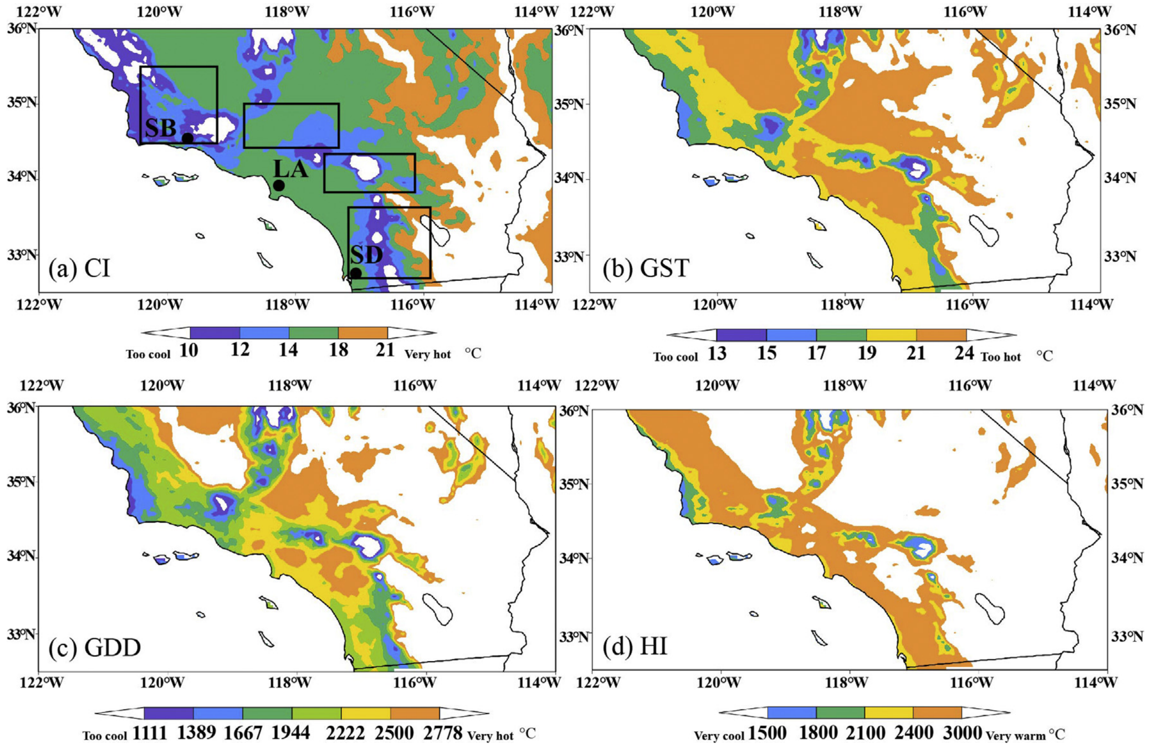

Fig. 5. Average bioclimatic indices for the period (1983–2012) based on classes from Table 1 (Bounding boxes in (a) indicate the winegrape growing regions. San Diego (SD) county, Los Angeles (LA) county, and Santa Barbara (SB) county marked for reference).

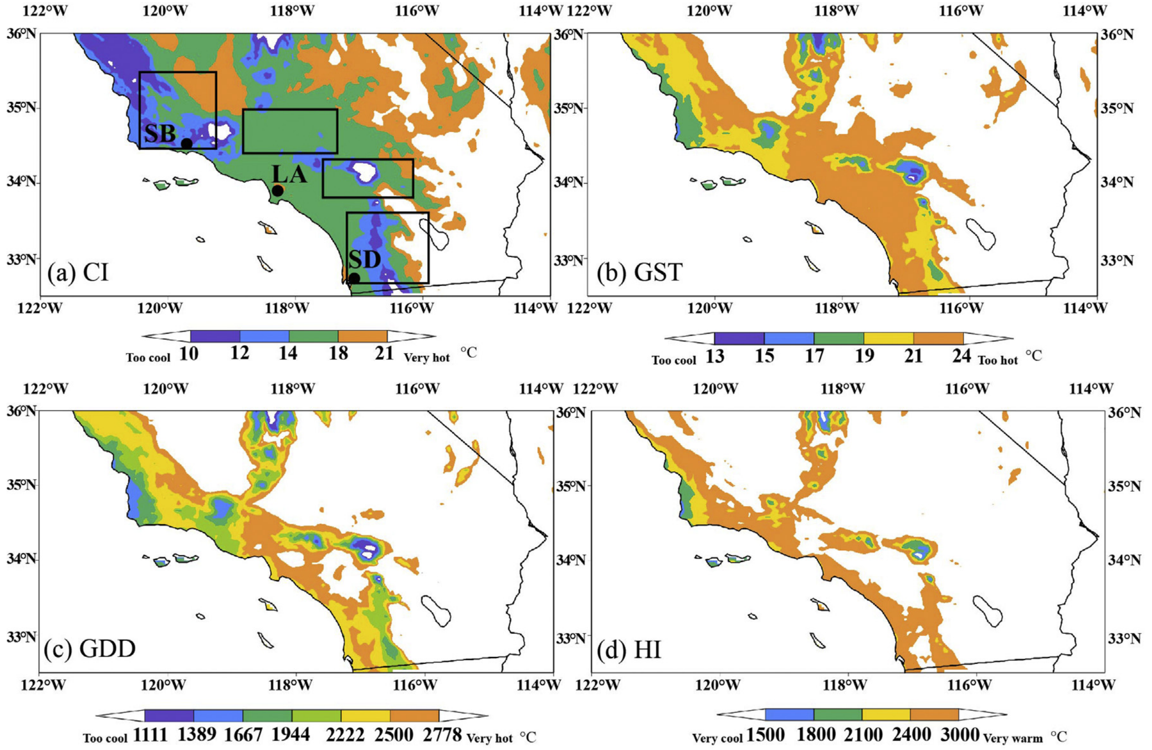

Fig. 6. Average bioclimatic indices the 2045–2050 period under the RCP8.5 climate warming scenario (Bounding boxes in (a) indicate the winegrape growing regions. San Diego (SD) county, Los Angeles (LA) county, and Santa Barbara (SB) county marked for reference).

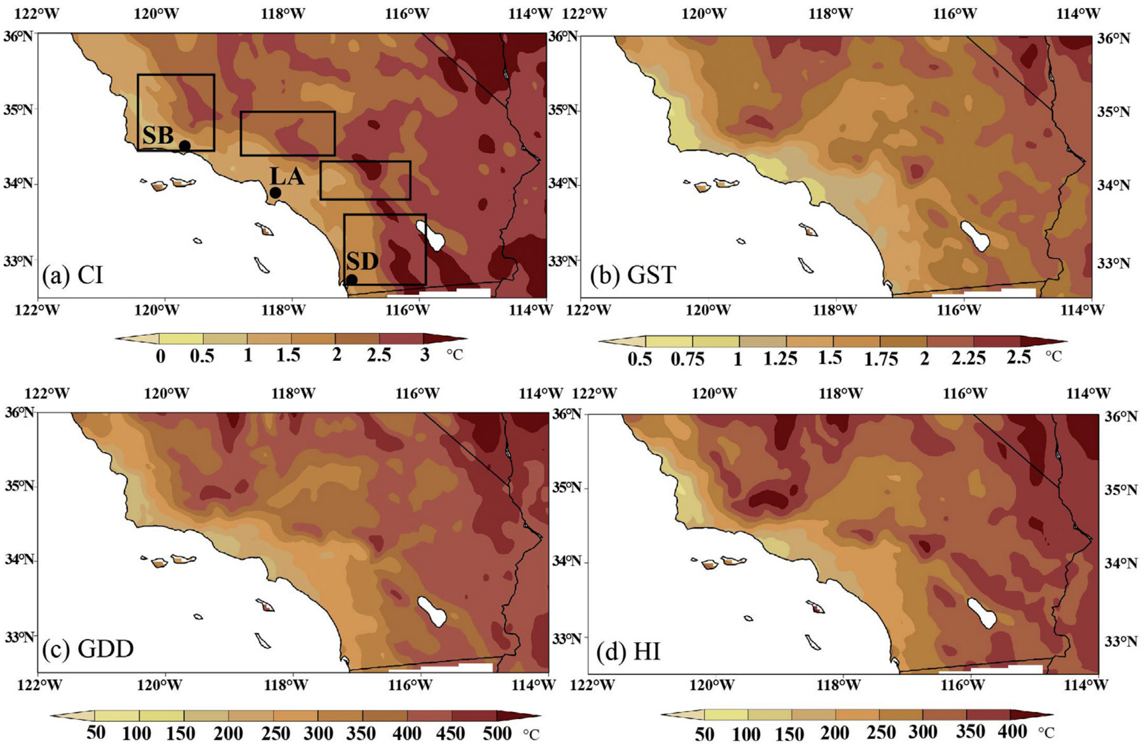

Fig. 7. Spatial change in indices from historical (1983–2012) to future (2012–2050) period based on the RCP8.5 warming scenario (Bounding boxes in (a) indicate the winegrape growing regions. San Diego (SD) county, Los Angeles (LA) county, and Santa Barbara (SB) county marked for reference).

increases in temperature and heat accumulation by mid-21st-century (Fig. 8). Regions either move closer to class thresholds or pass these thresholds into the warmest climate structures for winegrape crop cultivation (Table 3).

Projections of GST (Fig. 8b) imply that North region will transition from ‘hot’ to ‘very hot’ while South region will transition from ‘very hot’ to ‘too hot’ by 2050. South Central and North Central are still within the ‘very hot’ ranking, although South Central is slightly below the ‘too hot’ threshold. Southern regions have a higher average GST of approximately +1.8 °C when compared to the northern growing regions. Increases in GST suggest that southern California might reach the higher limits of quality wine production by mid-21st-century, based on established indices.

Increases in GDD of 258, 238, 256, and 265 °C for the growing season are projected for regions South, South Central, North Central, and North, respectively (Fig. 8). North Central and North regions transition into the second warmest climate group, according to the GDD class interval rankings, while South and South Central transition into the ‘too hot’ category, according to the upper threshold limit which was added to the GDD class intervals by Jones et al. (2010). North region experiences the greatest warming, with an increase in GDD during the growing season of 265 °C while South Central experiences the smallest of 238 °C.

Future projections of HI place all regions in the warmest climate structure of ‘very warm’. South, South Central, and North Central were previously within this ranking according to historic results, but North region transitions from ‘warm’ to ‘very warm’ with future warming (Fig. 8d). Average increases in heat units for growing regions is 207. Regions in the ‘very warm’ class might be at risk for increased stress on quality wine production, as temperatures continue to increase.

According to modeled future CI results (Fig. 8a), North Central region transitions from ‘cool nights’ to ‘temperate nights’ with an average of 15.2 °C, while South and South Central regions stay within temperate nights climate structure with an approximate average of 17.0 °C. North region rests on the threshold for temperate nights with an average of 14.1 °C during September nights and will most likely overcome the threshold with increased temperatures. As growing regions transition to warmer night temperatures, certain qualities may be lost, such as aroma for all varieties and coloring for red varieties (van Leeuwen and Darriet, 2016).

Changes in areal extent of climatic suitability based on bioclimatic indices show overall reductions in suitable land by mid-21st-century (Fig. 9). Across all winegrowing regions and indices, there is a reduction of nearly 42% in the cool to warm categories and an increase of approximately 30% in the warmest climate suitability category. Changes in GST extent show an average reduction of around 55% in the cool to warm categories for all regions. North Central and North regions display the largest relative reductions of around 100% for the coolest category of GST, GDD, and HI. South region extent increases roughly 100% in the warmest category for all indices, with up to 176% for GDD with a corresponding increase of around 2700 km^2.

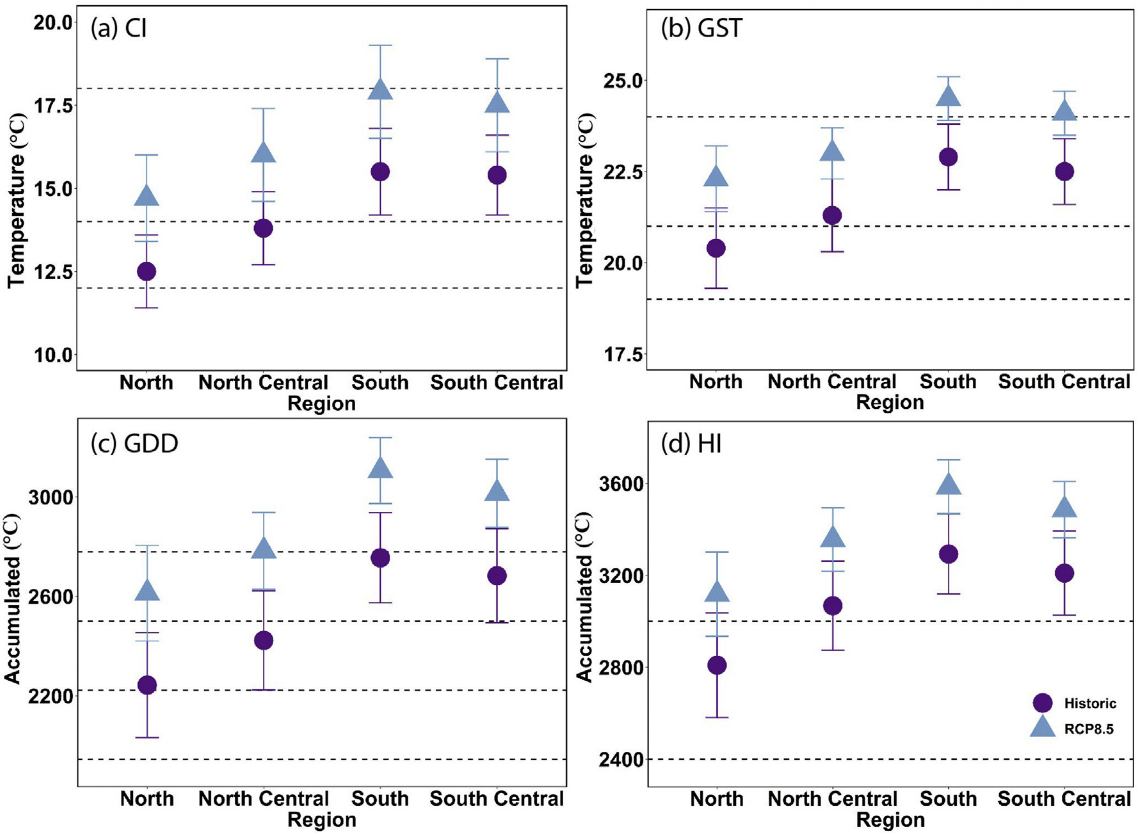

Fig. 8. Change in average indices from historical to future period based on the RCP8.5 warming scenario for 2041–2050 with index class breaks represented by dashed lines.

The largest changes in suitability areal extent are experienced by GDD and HI with approximately 8600 and 8700 km^2 of land, respectively. Our simulations suggest that there will be a reduction in the cool to warm climate suitability categories and an increase in the warmest category across all indices and regions, except HI where the warmest category extent decreases roughly 54% for South Central, North Central and North regions. This reduction in the warmest category is because the historical HI placed the regions in the warmest category, therefore as temperatures increase the change is experienced as a reduction in the 'very warm' (2400–3000 °C) class.

4. Discussion

Based on results from the WRF-SSiB future warming simulation, three central conclusions can be made about general temperature and precipitation trends for mid-21st-century. First, from 1983 to 2050 the decadal trend in average temperature is +0.38 °C. Second, the approximate change in mean temperature from historic (1983–2012) to future (2012–2050) is 1.2 ± 0.1 °C for all winegrape growing regions. Third, there are statistically significant decreases in precipitation for South, South Central, and North Central of up to −12% in monthly mean rainfall amounts. Change in average temperature could place stress on natural systems with regards to elevated heat accumulation and potential water stress due to reductions in precipitation (IPCC, 2018), which are conditions southern California is prone to experience.

Based upon the calculation of indices specific for determining the climate structure for winegrape suitability, five conclusions can be made about their status by 2050. First, there are increases in temperature and heat accumulation for all indices and all growing regions in southern California.

Table 3
Suitability class by region based on spatial average climate suitability indices for mid-21st-century (2045–2050).

Region	GDD	GST	CI	HI
South	Too hot	Very hot–too hot	Temperate–warm nights	Very warm
South Central	Too hot	Very hot–too hot	Temperate–warm nights	Very warm
North Central	Region VI–too hot	Very hot	Temperate	Very warm
North	Region V–too hot	Very hot	Cool–temperate	Warm–very warm

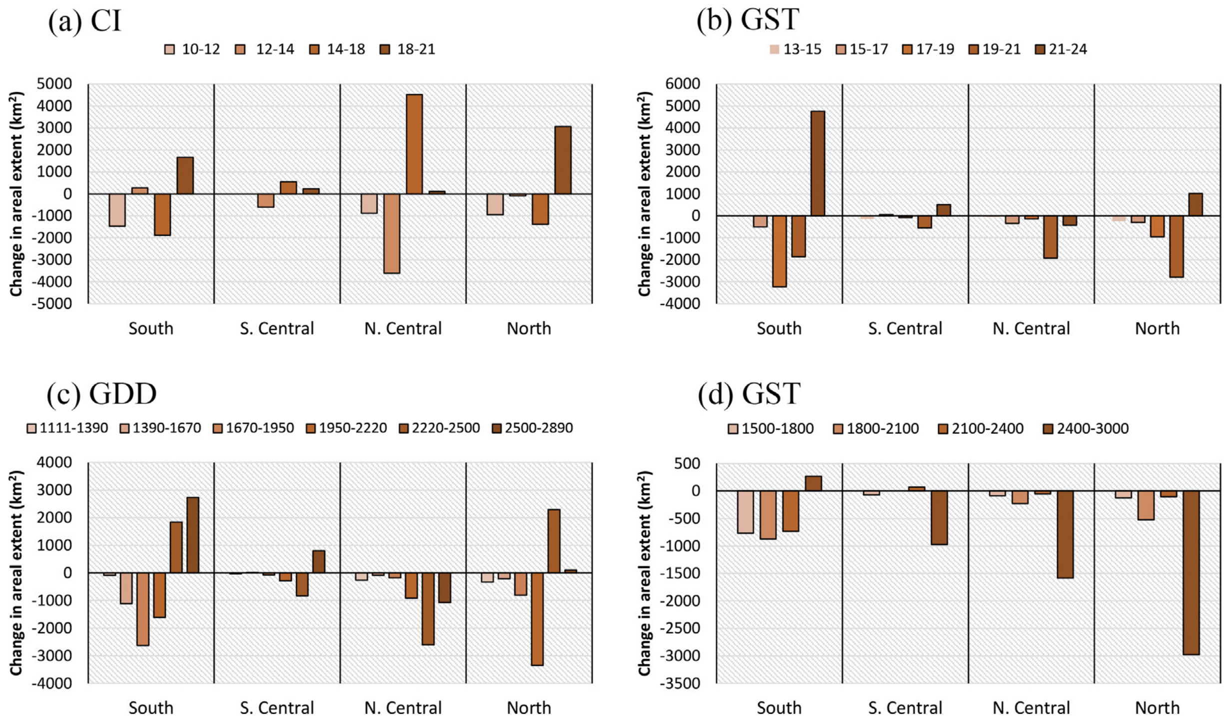

Fig. 9. Changes in bioclimatic indices areal extent between historical (1983–2012) and future (2045–2050) climate periods for the winegrowing regions in the study area (Negative values indicate reductions of areal coverage for a given climatic suitability category).

Second, results indicate a North-South temperature gradient with southern regions having a GST difference of approximately +1.8 °C when compared to the northern growing regions. Third, based on the calculation of HI, all regions are in the warmest climate structure by mid-21st-century (Table 3). This is most likely due to the increase in both average and maximum temperatures, which this index uses within its calculation. Fourth, GDD and CI experience the largest percent change across all regions and increase an approximate 10% in the future climate simulation. GST and HI increase an approximate 6% by mid-21st-century. These findings suggest that greater amounts of heat will be experienced during the months of April through October and that night temperatures in September also increase. Fifth, spatial suitability of climate indices reveals that by mid-21st-century there will be reductions in regions which can produce high quality wine and that most suitable regions will be found along the northern coastal regions and closer to mountain ranges. Reductions of approximately 8600 km^2 are projected for both GDD and HI by 2050. Although previous research has found that winegrape growing season and phenology has trended earlier with shorter phases (Webb et al., 2012; Jones, 2013; Vrsic et al., 2014), this study maintains the growing season and late ripening season time periods established by Tonietto and Carbonneau (2004) and Jones et al. (2010). This allows for robust comparison with research that has incorporated these indices into their results.

Continued increases in heat accumulation and decrease in precipitation could place additional moisture deficit stress to winegrape crops. Conditions in southern California are already very warm and dry, and based on results, these conditions are going to continue to mid-21st-century, which could impact the ripening stage of grapevines and ultimately lead to changes in wine composition and quality (van Leeuwen and Darriet, 2016; Mozell and Thach, 2014). Warmer temperatures could advance phenological timing by 1–2 months and create earlier budburst, flowering, veraison, and harvest (Keller, 2010; Cahill et al., 2007; Costa et al., 2016; Fraga et al., 2016). Earlier progression in winegrape maturity can expose the fruit to additional heat and stress throughout the year, which could lead to decreases in yield and threaten the wine typicity (degree to which a wine reflects its varietal origins) (Fraga et al., 2016). In addition, the critical ripening period will shift towards the hotter part of the season as phenological timing advances (Keller, 2010).

The consequence of this shift could have a substantial impact on the chemistry of the winegrape, including elevated sugars, lower acid concentrations, and lower anthocyanins producing potentially unbalanced wines (Keller, 2010; Jones, 2012; Duchêne, 2016). Elevated sugar levels could increase alcohol concentration while lower anthocyanins could reduce color intensity in red wines, impacting the aromatic properties (Keller, 2010; Mira de Orduña, 2010). Under very hot conditions, wine aroma and color can be impacted due to reduced metabolite accumulations (Mira de Orduña, 2010). These are the potential changes in winegrape phenology and chemistry that could lead to impaired wine quality and reveal two points of action.

This study highlights the need for collaboration between climate scientists and users of climate information to promote climate services. For instance, growers can have input on the use of indices to determine climate structures. Indices rely on general traits of the winegrape crop and growing season for all the Northern Hemisphere, but do not account for local variation. Growers can provide more detail on the growing season lengths, temperatures at which their varieties thrive, and whether the indices provide them with useful information for the future. This approach of incorporating users in the process of climate information has proven successful as information can be broadly used in adaptation to climate change (Kjellstrom et al., 2016; Street, 2016).

Additionally, the projected increase in temperature underscores the need for adaptive capacity within this sector to maintain wine identity and profitability (Bernetti et al., 2012). Galbreath (2011) found that a large wine firm in Australia implemented adaptive strategies to respond to climate change, such as: planting hotter climate varieties, purchasing land in cooler climates, sourcing grapes from cooler climates, subsurface water drip lines, recycled water, night irrigation, soil moisture monitoring, and even more adaptive techniques.

Also, to combat early ripening due to elevated temperatures, van Leeuwen and Darriet (2016) suggest that growers can change plant material to rootstock which have longer cycles and clonal selections with late-ripening. Cooling equipment is also recommended for regions with warmer temperatures, which might impact the sugar, potassium, acidity, and pH levels of the grape (Mira de Orduña, 2010). Blanco-Ward et al. (2019) suggests that it is possible to move vineyards to cooler sites, such as mountainous or coastal regions, but also warns that locations should be planned carefully to maintain freshwater sources and natural habitats. California wineries are replacing popular drip-irrigation methods with the practice of dry-farming. Locations that rely on dry-farming techniques typically receive approximately 300−500 mm of mean annual precipitation. Dry-farmed vines rely winter precipitation and methods aim to conserve soil moisture during dry periods through tillage, surface protection, and planting drought-resistant varieties (CAWSI, 2020). This technique is appealing to wineries in locations susceptible to drought and limited rainfall, like southern California.

This study suggests that winegrowers will need to adapt to a changing climate, to maintain wine quality and support the industry's growing economy. A study by Neethling et al. (2017) found that winegrowers place the greatest urgency on short-term strategies, including winemaking techniques, harvest management, soil management, canopy management, and pest and disease control. Long-term strategies were identified as a last resort and included changing grapevine varieties. These plans for adaptation can vary among regions and decisions to adapt are highly correlated to changes which are previously planned, and these are independent of climate change (Battaglini et al., 2009). Although change in southern California's climate is inevitable, there are many options for adaptation, and strategies have been proven successful, especially for locations that already experience a very warm climate. But emphasis should be placed on short- and long-term strategies if economic stability is desired.

5. Conclusion

This project generated a regional climate dataset to address potential changes to climatic suitability of winegrape for four regions containing 14 American Viticultural Areas in southern California by mid-21st-century. Climate structures are evaluated using four indices specific for the winegrape crop and include: the heliothermal index (HI), cool night index (CI), growing degree day (GDD), and growing season average temperatures (GST). Evaluation of indices reveal that regions transition into some of the warmest climate structures for viticultural purposes. Increases in mean changes between historic (1983−2012) and future (2012−2050) for HI, CI, GDD, and GST are roughly 7%, 11%, 10%, and 6%, respectively.

In addition, this study showed that by mid-21st-century there will be an approximate increase of 1.2 ± 0.1 °C in mean temperature and monthly mean rainfall amounts could decrease 11% ± 1.0% in southern California. By 2050, areal extent of regions across all indices will reduce an average 42% for the cool to warm climate suitability categories and increase an average 59% for the warmest category of GST, GDD, and CI. There will be an approximate reduction of 8700 km^2 in suitable land for winegrape cultivation extent based on the HI index due to warm average and maximum temperatures.

In general, North region experiences the coolest conditions, while South, South Central and North Central experience warmer nights and hotter GSTs. Suitable regions for mid-21st-century will be found along the northern coastal regions and closer to mountain ranges, where temperatures are more regulated. Based on current and projected conditions, most regions will be able to produce merlot, cabernet sauvignon, zinfandel, syrah, sangiovese, grenache, sauvignon blanc, chardonnay, and pinot noir varieties (among others). Apart from sauvignon blanc and pinot noir, most of these varieties prevail and thrive in moderate to hot climates and produce full-bodied wines. North region will be most suitable for production of cooler climate wines, like pinot noir and merlot.

Findings suggest growing regions will have some of the warmest climate for winegrape cultivation by mid-21st-century, but these results are not the final say for viticulture in southern California. There are many adaptation strategies available for mitigating very warm temperatures and low precipitation amounts, including planting hotter climate varieties, moving vineyards to coastal or mountainous regions, installing water drip lines and cooling equipment, dry-farming techniques, and implementing clonal selections with later-ripening.

This study provides a first-step into evaluation of changes to suitability for winegrape crop for southern California using a high-resolution atmosphere-biosphere coupled model, but future work should focus on 1) the continued improvement of climate model resolution, to capture the microclimates of local growing regions, 2) inclusion of more climate models and warming scenarios, 3) involving both climate scientists and users of climate information to promote climate services. Finally, this study provides information on vulnerability assessments that will support public policy and decision-making to guarantee local resilience to climate change impacts.

Declaration of competing interest

The authors declare no conflict of interest.

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