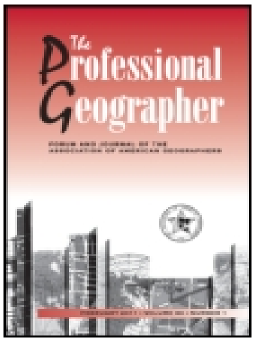

The Professional Geographer

ISSN: 0033-0124 (Print) 1467-9272 (Online) Journal homepage: https://www.tandfonline.com/loi/rtpg20

The Impact of Climate Change on the Viticultural Suitability of Maipo Valley, Chile

Megan Mills-Novoa, Philippo Pszczólkowski & Francisco Meza

To cite this article: Megan Mills-Novoa, Philippo Pszczólkowski & Francisco Meza (2016) The Impact of Climate Change on the Viticultural Suitability of Maipo Valley, Chile, The Professional Geographer, 68:4, 561-573, DOI: 10.1080/00330124.2015.1124788

To link to this article: https://doi.org/10.1080/00330124.2015.1124788

Published online: 18 Feb 2016.

The Impact of Climate Change on the Viticultural Suitability of Maipo Valley, Chile

Megan Mills-Novoa
University of Arizona

Philippo Pszczólkowski and Francisco Meza
Pontificia Universidad Católica de Chile

This study uses the case of the Maipo Valley in Chile to examine how climate change will affect viticultural suitability. Using a geographic information system analysis of topographic, soil, land use, and climate data, a baseline assessment of viticultural suitability in the Maipo Valley was performed. The impact of climate change on viticultural suitability was modeled by overlaying downscaled global circulation model temperature data for two emission scenarios. The findings of this study suggest that the capacity of vineyard managers in the Maipo Valley to cultivate high-quality traditional grape varietals from cooler grape maturity classes might be limited in the future. **Key Words: central Chile, climate change, GIS, viticultural suitability, wine.**

本研究运用智利迈坡谷的案例， 检视气候变迁如何影响葡萄栽植的可持续性。本研究运用地形、土壤、土地使用与气候数据的地理信息系统分析， 进行迈坡谷葡萄栽培可持续性的基线评估。本研究透过在两个温室气体排放方案中覆盖降尺度全球大气环流模型的气温数据，模式化气候变迁对于葡萄栽植可持续性的影响。研究结果发现，迈坡谷的葡萄园经理人，从较冷的葡萄熟成品种中培育出高质量的传统葡萄品种之能力, 在未来或许将会有所限缩。 **关键词: 智利中部, 气候变迁, 地理信息系统, 葡萄栽植的可持续性, 葡萄酒**。

En este estudio se utiliza el caso del Valle de Maipo, en Chile, para examinar cómo afectará el cambio climático la aptitud de viticultura. Usando un análisis de datos de topografía, suelos, uso de la tierra y climas, por medio de sistemas de información geográfica, se efectuó una evaluación estándar de la aptitud viticultural del Valle de Maipo. El impacto del cambio climático sobre esa aptitud fue modelado revistiendo datos de temperatura a escala reducida del modelo de circulación global para dos escenarios de emisión. Los descubrimientos de este estudio sugieren que en el futuro la capacidad de los administradores de los viñedos del Valle de Maipo para producir varietales de uva de la alta calidad tradicional a partir de clases de maduración más fresca podría ser limitada. **Palabras clave: Chile central, cambio climático, SIG, aptitud viticultural, vino.**

Within the last few decades there has been a growing consensus that anthropogenic greenhouse gas emissions have had and will increasingly have a significant impact on the Earth's climate (Intergovernmental Panel on Climate Change [IPCC] 2007, 2014). Viticulture, due to the narrow climatic range of high-quality wine grape production, is one of the agricultural sectors most vulnerable to the impacts of climate change. For this reason, it is critical to understand how viticultural suitability could be affected by changing climatic conditions in wine-growing regions under different climate change scenarios.

Recent research has projected that viticultural zones will shift 150 to 300 km poleward by 2049 and an additional 12 to 25 km poleward by 2099 under mid-range emission scenario projections (Jones 2007). Increases in mean annual temperature are the driver of these shifts and warming trends have already been detected within many wine-growing areas (Fraga et al. 2012; Koufos et al. 2014). Jones (2005) found that since 1950 there has been a 1.3°C and 1.4°C increase in winter and summer temperatures, respectively, in twenty-seven high-quality wine-producing regions. Hannah et al. (2013) found that there will be a 25 percent to 73 percent decline in area suitable for viticulture by 2050 in five major wine-producing regions globally.

Although the majority of the literature documents climate change impacts at a larger scale of resolution in an effort to generate global or country-level synthesis, far less work has been done to assess the variability present at a finer scale of resolution. In an effort to develop a methodological framework that offers results at a scale that is useful to practitioners and policymakers, we focused our study at the regional scale. Additionally, few studies have focused on the impact of climate on viticulture, an economically important industry within Chile. This project assesses the future impacts of climate change on the viticultural suitability of the Maipo Valley, contributing to the ongoing discussion of appropriate adaptation strategies for this

The Professional Geographer, 68(4) 2016, pages 561–573 © 2016 by American Association of Geographers.
Initial submission, July 2015; final acceptance, October 2015
Published by Taylor & Francis Group, LLC.

economically important region, which produces 12 percent of all wine in Chile (Servicio Agrícola y Ganadero [SAG] 2014).

Soil and climate are the main elements that have been used to define the concept of *terroir* (Vadour 2002) and characterize the viticultural suitability of a region. Among these elements, climate is the most critical factor in determining the capacity of a region to produce high-quality wine grapes (Seguin and De Cortazar 2005). Viticultural production is broadly limited to the growing season isotherms of 12°C to 22°C (Jones 2006). Additionally, large differences between daytime and nighttime temperatures favor the concentration of solutes and accumulation of sugars and acids that facilitate the cultivation of high-quality wine grapes. Optimal grape-growing locations such as central Chile have large diurnal temperature ranges of 15°C to 20°C.

Recognizing the importance of temperature, a wide number of bioclimatic indexes have been proposed using temperature as the most relevant variable for characterizing grape-growing suitability (Winkler et al. 1974; Huglin 1978; Gladstones 1992, 2011). These indexes have been applied to define viticultural regions at a global or country-level scale as in the case of Chile (Tonietto and Carbonneau 2004; Gil and Pszczólkowski 2015). These bioclimatic indexes, which match climatic characteristics to the capacity of an area to produce grape varietals with different climatic requirements, offer an important tool in assessing the impact of climate change on wine-growing regions.

Beyond the general poleward shift of viticultural zones and broad warming trend, the magnitude of climate change impacts on viticultural suitability will differ by region. White et al. (2006) projected that within the United States, premium wine grape production will decline by 81 percent corresponding to decreased productivity in current wine-producing regions. Wine-growing regions in Australia are also expected to significantly contract due to projected warming and have a limited capacity to shift, because many of these areas are currently in southernmost Australia and will be unable to shift further poleward (Hall and Jones 2008). Harvest dates within Europe are already occurring six to twenty-five days earlier, reflecting the strong relationship between phenological timing and warming (Jones 2005) and further studies have indicated a north and northwesterly shift in wine-growing regions within Europe due to climate change (Moriondo et al. 2013).

Despite Chile's role as the eighth largest producer of wine and fifth largest exporter of high-quality wine internationally, few studies have looked at the impact of climate change on wine production in Chile. Montes et al. (2012) characterized the climatic potential for viticulture in the Central Valley but did not integrate an analysis of climate change impacts. Central Chile is particularly vulnerable to the compounding impacts of water scarcity and elevated temperature due to climate change, making an analysis of climate change impacts on wine suitability critical for regional climate change adaptation planning and future scholarship. Warming trends have already begun to impact Chilean wine-growing regions. Between 1933 and 1992, warming rates of 1.3°C to 2.0°C were detected by several weather stations within Chile (Rosenbluth, Casassa, and Fuenzalida 1997). More recent data have shown that temperature trends are spatially heterogeneous, with 0.2°C per decade cooling at coastal stations and 0.25°C warming in the Andes (Garreaud and Falvey 2009).

The purpose of this study is to assess the current and future viticultural suitability of the Maipo Valley in the Central Valley of Chile. Soil, topographic, land use, and historical weather data were used to create a baseline assessment. Two IPCC emissions scenarios and corresponding global circulation models (GCMs) were then used to assess future viticultural suitability for three thirty-year normals. Ultimately, this project assesses the future impacts of climate change on the viticultural suitability of the Maipo Valley, contributing to the discussion of appropriate adaptation strategies for this region that has experienced a tremendous 260 percent growth in the extent of vineyards since 1997 (SAG 2013).

The study seeks to integrate and synthesize geographic and biophysical data at the scale of one denomination of origin, the legal delineation of a wine-growing region, and the broader, corresponding water basin to provide an analysis at a level that is relevant for practitioners and policymakers. Additionally, this study builds on the methodology of assessing composite viticultural suitability through the integration of topographic, soil, land use, and temperature data and integrates this assessment into a characterization of projected climate change impacts on the viticultural conditions within the region. The similarities between Maipo Valley and other high-quality wine-producing regions such as California, Australia, and South Africa make this study highly relevant to understanding the vulnerability of the world's most significant wine-producing regions to a changing climate.

Materials and Methods

Study Area

The Chilean viticultural area of Maipo Valley was included in this study as delineated according to the Chilean wine appellation of origin system (Figure 1). Maipo Valley is located in the Central Valley of Chile between latitudes 32°55′ and 34°15′ S and encompasses the metropolitan area of Santiago. There are three distinct regions within Maipo Valley: Alto Maipo in the foothills of the Andes, Central Maipo on the valley floor, and Coastal Maipo. Within Maipo Valley, 12,679 ha are cultivated for viticultural purposes with the principal varietals cultivated being

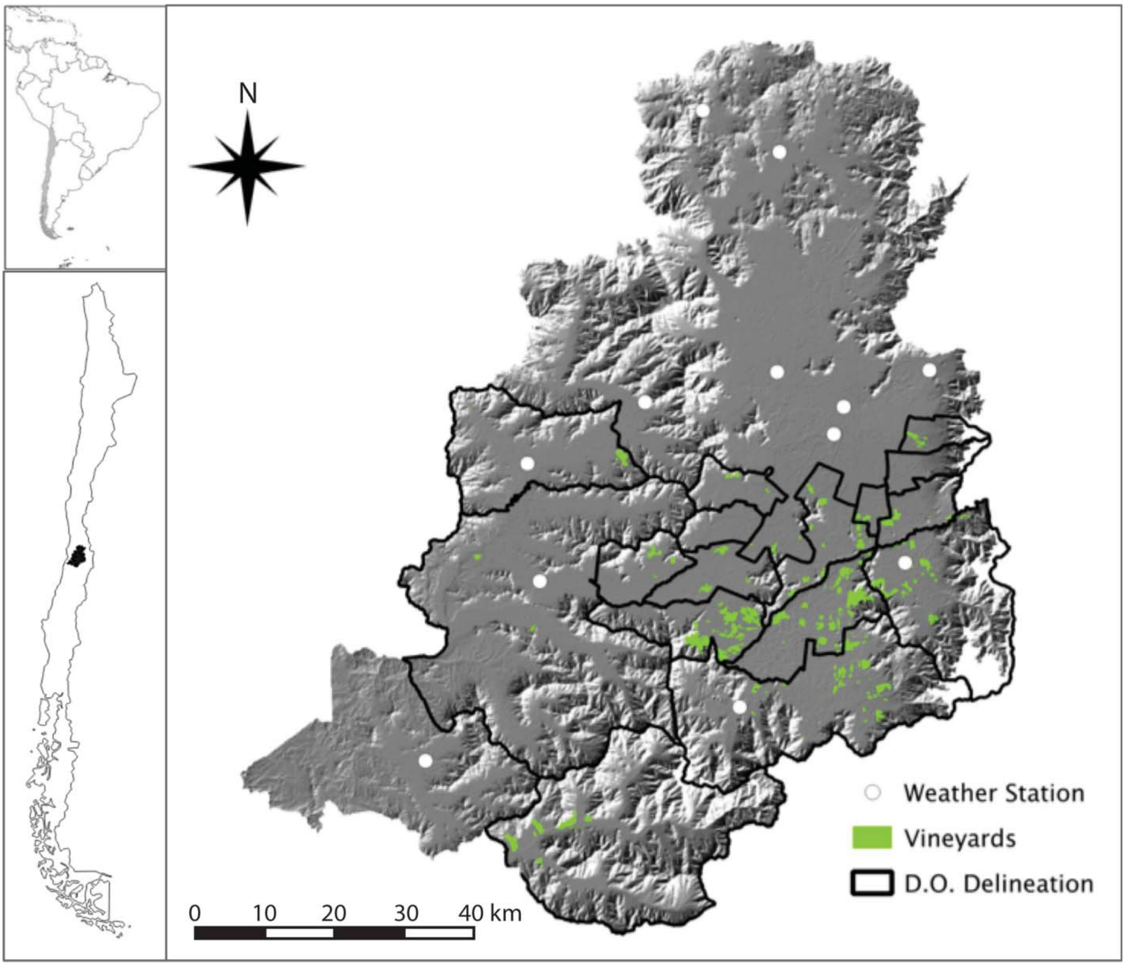

Figure 1 *Distribution of surveyed vineyards in the Maipo Valley denomination of origin and Maipo Valley weather stations. (Color figure available online.)*

Cabernet Sauvignon (52.2 percent of surface), Merlot (9 percent), Syrah (8.5 percent), Chardonnay (7.5 percent), Carmenere (7 percent), Sauvignon Blanc (5.3 percent), and Cabernet Franc (2.1 percent; SAG 2011). Vineyards are generally cultivated with the use of irrigation, with approximately 60 percent of all vineyards relying on surface water for irrigation and the remaining 40 percent using groundwater. This region is characterized by a Mediterranean climate with maximum temperatures ranging from 25°C to 35°C during the growing season (October–April) and with large diurnal temperature ranges throughout the year. Thermal accumulation is around 1,550 degree days (Merlet, Castillo, and Santibañez 1987). Mean annual precipitation increases toward the Andes, varying from 456 mm (Buin) to 736 mm (Puente Alto-Pirque), although 80 percent of precipitation occurs in winter.

Within this study, the entire Maipo River basin in addition to the Maipo Valley denomination of origin was included because vineyard development has continued to extend beyond the formal Maipo Valley denomination of origin. Additionally, this study sought to assess future viticultural suitability and therefore areas within the river basin not currently under cultivation were considered, because these areas might become potential grape-growing sites based on projected climate change impacts. All analyses were done at the scale of the Maipo River basin below 2,000 m (to exclude mountainous areas) to capture future potential viticultural zones.

Topographic Suitability

To characterize the baseline viticultural suitability of Maipo Valley, a multistage geographic information system (GIS) analysis was performed, incorporating factors related to topography, soils, land use, and climate. To establish an understanding of the geographic

Table 1 *Topographic suitability class rankings used in categorizing the suitability of the landscape for wine grape cultivation*

Elevation (m)	Class rankings	Slope (%)	Class rankings	Solar radiation (kilowatts/m^2)	Class rankings
0–900	2	<1	0	550–1,010	−2
>900	−2	1–5	1	1,010–1,107	−1
		5–15	2	1,107–1,173	0
		15–30	1	1,173–1,262	1
		>30	−1	1,262–1,496	2

features of existing individual vineyard sites, a comprehensive GIS database of vineyard locations was created (Jones, Sneed, and Nelson 2004). The survey of Maipo Valley vineyard sites was conducted using Google Earth imagery and aerial photography. Vineyard locations were then verified through site visits and the use of a Global Positioning System (GPS). The locational data gathered, as well as conversations with wine makers and vineyard managers, were used to define the topographical characteristics of ideal sites for grape growing in the valley (Jones, Sneed, and Nelson 2004).

The topographic suitability was assessed through the use of a 30-m-resolution digital elevation model (DEM). The entire extent of the Metropolitan Region, which encompasses Maipo Valley, was then categorized for the most advantageous slope, elevation, and solar radiation. The composite topographic viticultural suitability was constructed through a multilayer, topographically driven potential site analysis using ArcGIS (ArcGIS, Version 10, Esri, Redlands, CA, USA) with class rankings given to the respective topographic factors characterized in each grid (Table 1). The elevation ranking was determined through the use of in-field observations as well as the distribution of the average elevation of current vineyards as determined through the initial survey of vineyard sites. The high elevation threshold reflects the presence of high-quality vineyards in the foothills of the Andes, residing in the eastern extent of the region. Slopes were categorized into five classes (Table 1). A calculation of solar radiation was used instead of aspect to account for the seasonal variation in solar declination and azimuth. A solar radiation index was calculated every thirty days at two-hour intervals during the growing season (October–April) using the ArcGIS spatial analysis solar radiation tool. Solar radiation values were reclassified based on the statistical distribution of radiation values (Santibañez 1992; Jones, Sneed, and Nelson 2004). The three separate suitability grids were then summed to create a single topographic suitability layer.

Soil Suitability

To analyze the soil suitability of the Maipo Valley, data from Centro de Información de Recursos Naturales (CIREN) were used. Site suitability was analyzed based on four soil properties: depth to bedrock, total available water, pH, and drainage (Margarey, Seem, and DeGloria 1998). An average value for all four properties was established for each soil group.

Drainage is widely regarded as the most important factor in determining vine success and is influenced by variables such as texture, depth, slope, and aspect (Cass 1999). Chilean soil surveys present drainage classifications using six classifications ranging from very poorly drained to excessively drained. Soil groups were characterized by their drainage class and given corresponding suitability rankings (Table 2). In dry growing regions, such as the Maipo Valley, the depth to bedrock indicates the vine's ability to cope with dry periods (Dry and Smart 1988). Soil groups were characterized by their depth and given a corresponding suitability ranking.

Total available water (TAW) is a property that factors in both the available water holding capacity as well as the effective root depth of soil and indicates the capacity of vines to tolerate moderate drought. The mean available water holding capacity for each soil group was calculated and then weighted by the percentage of each component per map unit. Soil groups were characterized by their respective class ranking (Cass, Hansen, and Dowley 2002). Soil pH is an indication of soil fertility and nutrient balance. A mean value was calculated for each soil group and then

Table 2 *Soil suitability class rankings used in categorizing the suitability of soil for wine grape cultivation*

Soil depth (cm)	Class rankings	pH	Class rankings	Drainage (class)	Class rankings	Total available water	Class rankings
<63	2	<6	−1	6	0	>200	−1
>63	−2	6–8	1	5	1	150–200	0
		>8	−1	4, 3	0	100–150	1
				2,1	−1	50–100	0
						<50	−1

weighted by the percentage of each component per map unit. Three classes were established, with ideal vineyard soils having a pH between 6 and 9 (Cass, Hansen, and Dowley 2002).

The four soil property suitability grids were then were combined using a weighted sum with drainage being given the greatest weight (40 percent) and the other factors weighted equally (20 percent), reflecting the relative importance of these soil properties in determining vine success (Jones, Sneed, and Nelson 2004). A final soil suitability composite grid was produced from the weighting of the four soil properties.

Land Use Suitability

Within the Maipo Valley, land use is a key determinant in assessing viticultural potential. Santiago, which is adjacent to the Maipo Valley denomination of origin, is an expanding metropolitan area, and formerly agricultural land has been converted to land uses that are not conducive to viticultural production (residential, industrial, commercial, etc.). The urbanized surface area of Santiago and outlying towns was extracted from the data set because these areas no longer have viticultural potential.

Baseline Climatic Suitability

To assess climatic suitability, a composite climate model was generated using three factors: varietal suitability, irrigation need, and risk for extreme weather events. Temperature data from eight weather stations within Maipo Valley with an average eighteen-year record length were used to calculate all variables. Weather stations within Santiago were excluded from the study due to urban heat island impacts and low viticultural suitability in these areas. Station temperature data were corrected using a factor of 0.6°C per 100 m (equivalent to the mean temperature lapse rate) to better represent climatic conditions of vineyards residing at higher elevation but within the same *comuna* as the station (Gladstones 2011). If no vineyards were located within the *comuna* of a given weather station, then the average vineyard elevation within the total study area was used. Temperature data were only corrected for elevation for one weather station (Rungue Embalse), whereas all other weather stations were located at the approximate elevation of the average vineyard within that area.

To calculate varietal suitability, biologically effective degree days (BEDD) were calculated to estimate the phenological fit of grape varietals to model climatic conditions within Maipo Valley. The use of a BEDD index enables sites to be characterized by climate maturity classes that categorize grape varietals by optimal heat summation ranges. The BEDD index developed by Gladstones (2011) was used for climate maturity class designation (see Table 3). BEDD calculates heat summation while incorporating an adjustment for diurnal temperature range and a day length correction factor (Hall and Jones 2010; Gladstones 2011):

$$\sum_{\text{October 1}}^{\text{April 30}} \min[\max([T_{\max} + T_{\min}]/2 - 10, 0)K + TR_{\text{adj}},\ 9]$$

where

$$TR_{\text{adj}} = \begin{cases} 0.25[T_{\max} - T_{\min} - 12], & [T_{\max} - T_{\min}] > 12 \\ 0, & 10 < [T_{\max} - T_{\min}] < 12 \\ 0.25[T_{\max} - T_{\min} - 10], & [T_{\max} - T_{\min}] < 10 \end{cases}$$

and K is an adjustment for latitude/day length and was calculated according to Gladstones (2011). BEDD values were then interpolated using the inverse distance weighting (IDW) function within ArcGIS because this interpolation method produced the lowest level of error when compared to kriging and other interpolation techniques. BEDD values were then reclassed by corresponding grape variety climate maturity classes (Jones 2006; Gladstones 2011).

Irrigation need was calculated for the study area with the use of the Hargreaves evapotranspiration equation, which was selected because of data

Table 3 *Representative white and red grape varietals classified by climate maturity class and the corresponding biologically effective degree days requirement needed for grape maturation*

Climate maturity class	BEDD required	White grape varietals	Red grape varietals
1	1,020	Bouveir, Madeline, Optima, Ortega	
2	1,080	Muscat Ottonel, Seyval Blanc	Meunier, Zweigelt
3	1,140	Chardonnay, Pinot Gris, Sauvignon Blanc	Pinot Noir, Tinta Amarella
4	1,200	Aligoté, Riesling, Semillion	Malbec, Tempranillo, Zinfandel
5	1,260	Viognier, Arneis, Taminga	Cabernet Franc, Merlot, Syrah (Shiraz)
6	1,320	Colombard, Folle Blanche, Macabeo	Cabernet Sauvignon, Sangiovese, Tannat
7	1,380	Gros and Petit Manseng, Mauzac, Trebbiano	Carmenère, Petit Verdot, Grenache
8	1,440	Grenache Blanc, Verdicchoa	Aglianico, Aramon, Canaiolo, Carignan,
9	1,500	Biancone, Bombino Bianco, Doradillo	Negroamaro, Tarrango

Note: BEDD = biologically effective degree days.

availability within the region (Allen et al. 1998):

$$ET_0 = 0.0023(T_{\mathrm{mean}} + 17.8)\sqrt{(T_{\mathrm{max}} - T_{\mathrm{min}})}R_a,$$

where R_a is extraterrestrial radiation (MJ $\mathrm{m}^{-2}\mathrm{day}^{-1}$). Within this study, relative evapotranspiration levels within the basin are most important when estimating relative irrigation need. Evapotranspiration values for weather stations were interpolated using IDW and reclassed into three suitability classes according to the relative rate of evapotranspiration.

Risk was calculated by summing the number of days with extreme heat events of maximum temperatures above 35°C (White et al. 2006). Within Maipo Valley, frost damage is not a significant concern and therefore extreme heat was the only climate risk value considered. Days of extreme heat were interpolated using IDW and values were reclassed according to relative heat risk. Areas that experienced more than three days with maximum temperatures exceeding 35°C were ranked as being high-risk areas.

Chilling hours or hours with temperatures below 7°C were also assessed for both baseline and projected temperature records. Due to the relatively low chilling hour requirement of grapevines and the high diurnal temperature range in Maipo Valley, chilling hours was not a significant limiting factor and was not included.

Composite Baseline Viticultural Suitability

The four site factors—topography, soil, land use, and climate—were then combined by summing the composite suitability rasters. The composite suitability grid was then masked with the climate maturity class grid to create a final data set that depicts the relative viticultural suitability by climate maturity class.

Projected Climatic Suitability

Within this study, the bias-correction and spatial downscaling method of Wood et al. (2004) was used, because it is quantitatively efficient and performed well when applied to studies that downscaled extended GCM simulations for impact analyses (Hayhoe et al. 2004; Maurer and Duffy 2005; Maurer et al. 2007). This method is an empirical statistical technique in which monthly precipitation and temperature output from a given GCM is downscaled using quantile-based mapping (Panofsky and Brier 1968) of the probability density functions for a monthly GCM temperature onto those of gridded observed data. Temperature data from all eight weather stations were downscaled for scenario A1B and B1 using seven GCMs. The A1B emissions scenario assumes "balanced" growth and land use changes, whereas the B1 emission scenario assumes a world development path that "favors efficiency of resource use and 'dematerialization' of economic activities" (IPCC 2000, 188).

The seven GCMs were chosen because they were representative of a range of distinct GCMs suited to southern South America, allowing for an analysis of the range of uncertainty within the downscaling process (Meehl et al. 2007; Marengo et al. 2009). The GCMs and related IPCC AR4 emission scenarios used in the analysis were chosen because the majority of analysis was conducted prior to the release of the AR5 emission scenarios. Knutti and Sedlacek (2013) found that the IPCC AR5 climate models were very similar to the AR4 models with consistent temperature and precipitation patterns. The AR5 representative concentration pathways (RCPs) are significantly different than the AR4 emission scenarios in that they represent a wider range of possible future outcomes. In the scope of this study, though, we sought to examine the impact of midrange emission scenarios on viticulture and therefore the use of AR4 emission scenarios still allows for a robust analysis of these impacts.

An average temperature was calculated by averaging the outputs of the seven GCMs for a given month. Daily values for GCMs are generated by randomly selecting historical months and creating a daily record that mirrors historical temperature variation but is rescaled using an additive factor according to projected monthly average temperatures (Wood et al. 2004). Minimum and maximum daily temperatures were calculated by importing historical daily maximum and minimum temperatures into the downscaling model.

Based on the daily minimum, maximum, and average temperatures that were calculated through the downscaling process, the climatic variables of evapotranspiration, BEDD, and days with maximum temperatures exceeding 35°C were subsequently calculated for comparison with historical values. These values were calculated for three thirty-year normals—2010 to 2040, 2040 to 2070, and 2070 to 2100—under two IPCC emission scenarios. Projected climate variables were interpolated using IDW and rasters were reclassed according to the suitability rankings and climate maturity classes detailed earlier.

Composite Projected Viticultural Suitability

The four site factors—topography, soil, land use, and projected climate—were then combined for both the scenario A1b and B1 downscaled data over the three climate normals by summing the composite suitability grids for each factor according to their individual grape-growing influence as detailed earlier. The composite suitability grids were then masked by the corresponding climate maturity class grid to create a final data set that depicts the relative viticultural suitability of sites by climate maturity class for both climate change scenarios for all three climate models and a control. Based on these rasters, land area data were extracted to infer the changes in grape-growing suitability zones within Maipo Valley. The methodological framework used in this study is represented schematically in Figure 2.

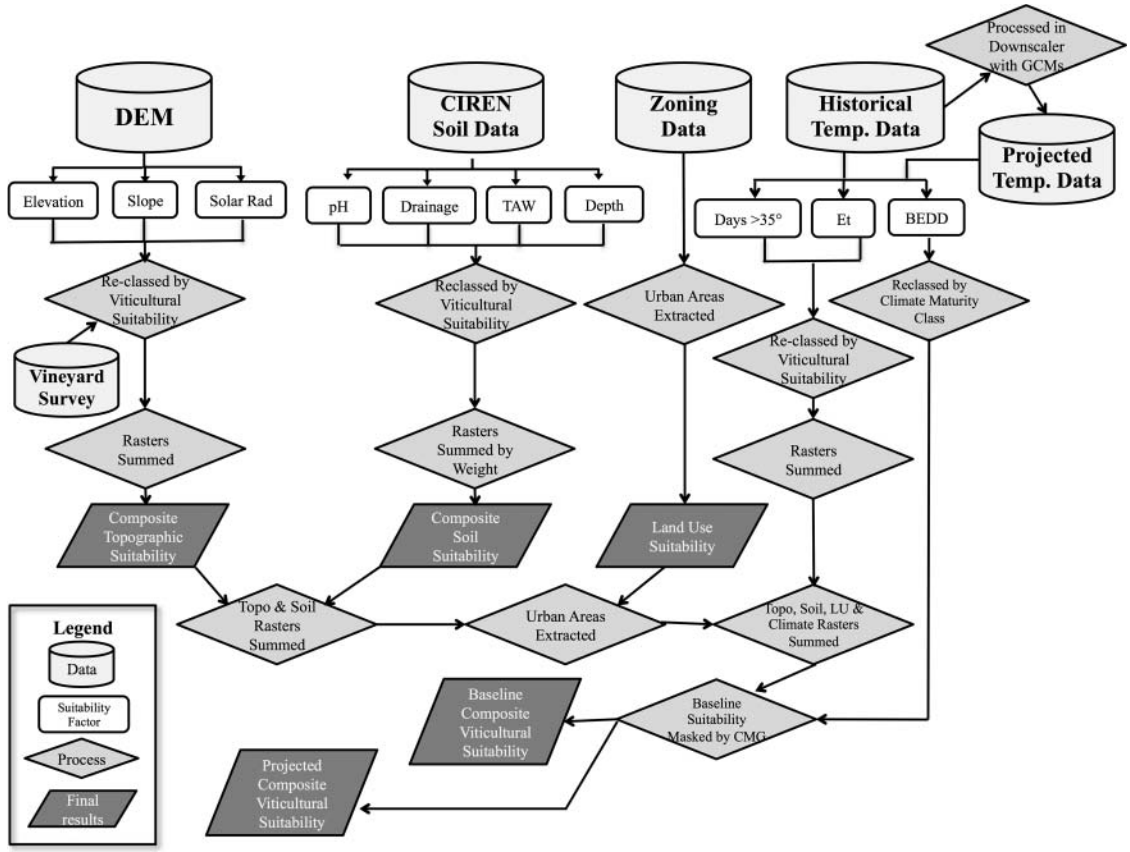

Figure 2 *Methodological flowchart: Assessing the baseline and projected composite viticultural suitability of the Maipo Valley. Note: DEM = digital elevation model; CIREN = Centro de Informacíon de Recursos Naturales; GCM = global circulation model; TAW = total available water; BEDD = biologically effective degree days.*

Results

Baseline Viticultural Suitability

In the Maipo Valley denomination of origin, the vineyards surveyed encompassed 96.44 km^2 across fifteen *comunas*, which are regional subdivision units within Chile (Figure 1). Two hundred and twenty-two vineyard tracts were surveyed. The average elevation of vineyards was 480 m and vineyards were found at elevations ranging from 123 m to 835 m. Vineyard slopes ranged from 26.8 percent to essentially flat, with an average slope of 5.7 percent. The elevation and slope values of vineyards were clustered by region, with many of the high-elevation, high-slope vineyards residing in the foothills of the Cordillera. Within the Maipo Valley, 69.8 percent of all land was found to have high or intermediate-high topographic suitability, with only 23.6 percent of all land being categorized as having low or intermediate-low suitability (Figure 3). Much of the land that was topographically unsuitable was found in the steep foothills of the Cordillera.

A total of 86.9 percent of the Maipo Valley was found to have high or intermediate-high soil suitability (Figure 3). The highest scoring soils were found on the valley floor and among the low-lying hills. A total of 665.8 km^2 were categorized as having no viticultural suitability due to urban land use (Figure 3).

The topographic, soil, and land use suitability data sets were then summed to produce a baseline scale of suitability. Of land in the Maipo Valley, 8.6 percent was classified as having high viticultural suitability, 45.9 percent with intermediate-high viticultural suitability, 27.9 percent with intermediate suitability, and 17.6 percent with intermediate-low or low viticultural suitability (Figure 3).

Climatically, no portion of the study area was found to have heat summation values outside of the suitable range for maturing high-quality wine grapes, although there was a significant range of climate maturity classes represented, with 12.4 percent of Maipo Valley designated as Class V, 33.8 percent as Class VI, 38.5 percent as Class VII, and 15.3 percent as Class VIII (Figure 3). The hotter classes were found in the northern, more arid portion of the valley, with cooler classes found in the eastern and western borders of the

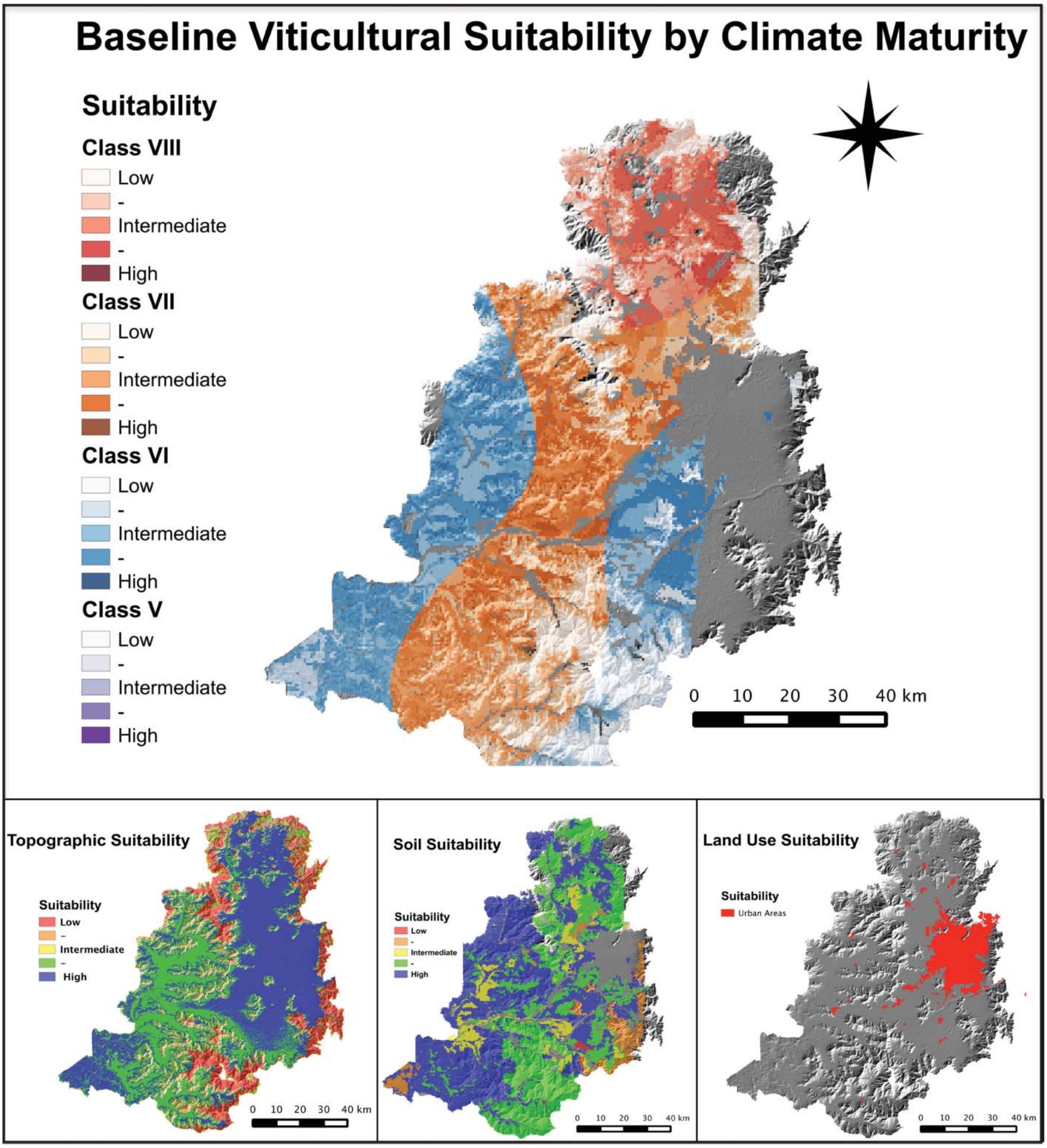

Figure 3 *The baseline topographic, soil, land use, and composite viticultural potential by climate maturity class of the Maipo Valley. (Color figure available online.)*

valley, where higher elevation vineyards enjoy cooler temperatures as well as the cooling effect of the nearby coast. Across climate maturity classes, fairly consistent distributions of high to low suitability rankings were found.

Projected Viticultural Suitability

The projected climatic analysis found across scenarios and models that temperatures increased by the mid-century (Table 4). As related to viticultural suitability, climate maturity classes became more prevalent through time and in both scenarios (Figure 4). Among the A1B scenario, which is the more severe scenario, the east–west and north–south temperature gradient is still visible in the early scenarios but becomes classified as uniformly climate maturity Class IX. Scenario B1 as well as the control initially underestimated the heat summation occurring in the eastern portion of the valley, but in B1, hotter climate maturity classes progressively become more prevalent through time, although never reaching the severity modeled in A1B (Figure 4).

Beyond shifting climate maturity class suitability through time, a subtle change in overall viticultural

Table 4 *Projected temperature changes under the seven downscaled global circulation models used in this study for three climate normal*

	A1B-Early		A1B-Int.		A1B-Late		B1-Early		B1-Int.		B1-Late	
Model	**Avg. temp**	**± Historical**	**Avg. temp**	**± Historical**	**Avg. temp**	**± Historical**	**Avg. temp**	**± Historical**	**Avg. temp**	**± Historical**	**Avg. temp**	**± Historical**
CCMA	15.43	0.60	16.30	1.47	16.81	1.97	15.27	0.44	15.80	0.97	16.26	1.42
GFDL	15.22	0.39	16.06	1.22	16.79	1.96	14.87	0.04	15.57	0.74	15.81	0.97
GISS AOM	15.16	0.32	15.85	1.02	16.88	2.05	14.97	0.14	15.50	0.66	16.15	1.31
mpiECHAM	15.02	0.19	16.20	1.37	17.53	2.70	14.78	−0.06	15.79	0.96	16.50	1.66
mriCGCM	15.03	0.19	15.70	0.86	16.31	1.48	14.83	−0.01	15.31	0.48	15.65	0.82
niesMIRO	15.54	0.71	16.93	2.10	18.10	3.26	15.43	0.59	16.32	1.49	17.08	2.24
HadCM3	15.43	0.60	16.33	1.50	17.29	2.46	15.24	0.40	15.84	1.01	16.51	1.68

Note: CCMA = Canadian Centre for Climate Modelling and Analysis; GFDL = Geophysical Fluid Dynamics Laboratory; GISS AOM = Goddard Institute for Space Studies Atmosphere-Ocean Model; mpiECHAM = Max Planck Institute for Meteorology; mriCGCM = Meterological Research Institute, Japan; niesMIRO = Center for Climate System Research, National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan; HadCM3 = Hadley Centre for Climate Prediction and Research.

suitability was observed (Table 5). This worsening viticultural suitability reflects the impact of increased temperatures on irrigation need and risk due to extreme high temperature events, both of which are suitability parameters.

Discussion

The projected viticultural suitability models show a consistent trend toward warmer climate maturity classes, suggesting that the ability of vineyard managers to produce high-quality grapes from cooler climate maturity classes might be limited in the future. BEDD is not ideal for assessing if a region is unsuitable for viticultural production due to high temperatures because vineyard managers might choose to harvest varietals earlier when the necessary heat summation has occurred (Hall and Jones 2010). The quality of grapes harvested earlier might be reduced, however, because phenological development can be rapid and produce unbalanced wines due to earlier sugar ripeness and loss of acidity through respiration (Jones, Sneed, and Nelson 2004; Keller 2010). Although methodologically different, the results of this study are

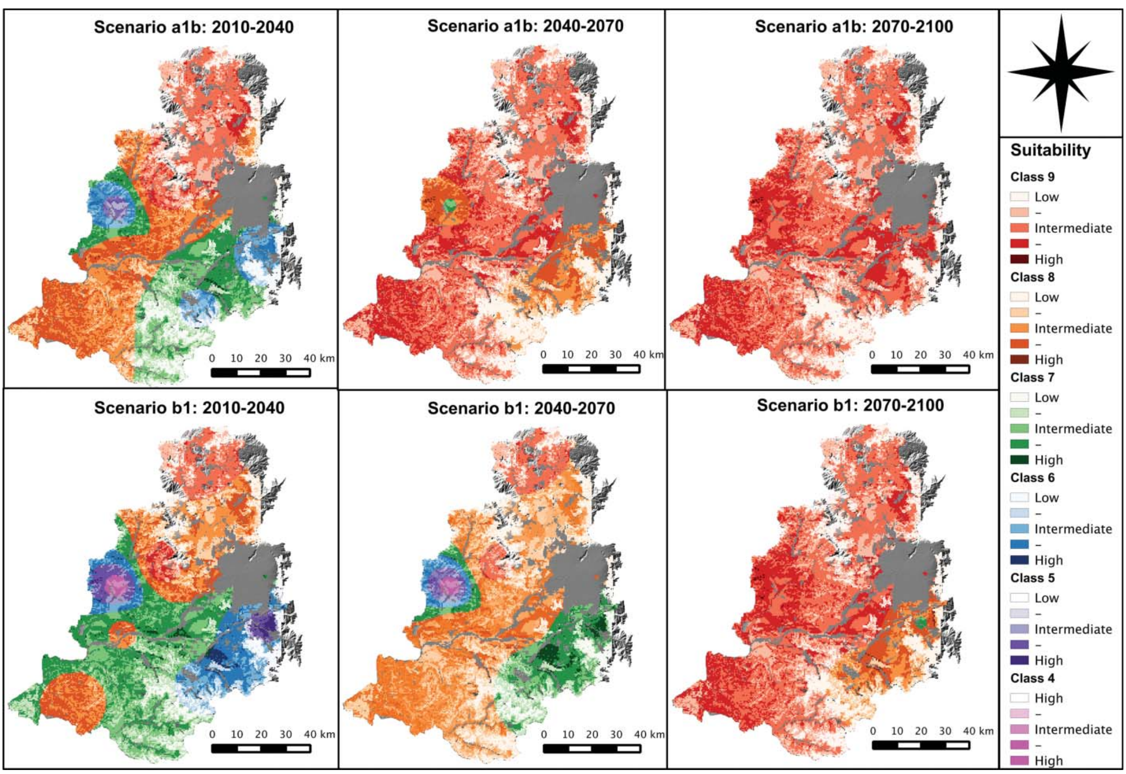

Figure 4 *Projected composite viticultural suitability by climate maturity class under emissions scenarios A1B and B1 in three climate normal periods. (Color figure available online.)*

Table 5 *Baseline and projected composite viticultural land area statistics by climate maturity class*

Climate maturity class	Historical		Control		A1B-Early		A1B-Int.		A1B-Late		B1-Early		B1-Int.		B1-Late	
	Total area (km^2)	%	Total area (km^2)	%	Total area (km^2)	%	Total area (km^2)	%	Total area (km^2)	%	Total area (km^2)	%	Total area (km^2)	%	Total area (km^2)	%
Class IV (1200)																
Low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low-intermediate	0.00	0.00	33.24	9.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Intermediate	0.00	0.00	80.99	22.14	0.00	0.00	0.00	0.00	0.00	0.00	25.36	41.99	22.32	47.07	0.00	0.00
High-intermediate	0.00	0.00	196.12	53.61	0.00	0.00	0.00	0.00	0.00	0.00	34.79	57.61	24.86	52.42	0.00	0.00
High	0.00	0.00	55.47	15.16	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.40	0.24	0.51	0.00	0.00
Area/ of region	0.00	0.00	365.83	5.68	0.00	0.00	0.00	0.00	0.00	0.00	60.39	0.94	47.42	0.75	0.00	0.00
Class V (1260)																
Low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low-intermediate	67.05	13.06	331.54	24.75	0.00	0.00	0.00	0.00	0.00	0.00	11.48	3.83	0.00	0.00	0.00	0.00
Intermediate	195.01	37.98	387.84	28.95	28.27	37.39	0.00	0.00	0.00	0.00	64.30	21.47	29.20	22.85	0.00	0.00
High-intermediate	239.17	46.58	434.58	32.44	47.10	62.29	0.00	0.00	0.00	0.00	179.46	59.91	95.83	74.99	0.00	0.00
High	12.19	2.37	185.84	13.87	0.24	0.32	0.00	0.00	0.00	0.00	44.32	14.79	2.76	2.16	0.00	0.00
Area/ of region	513.42	8.08	1,339.79	20.80	75.61	1.20	0.00	0.00	0.00	0.00	299.55	4.66	127.79	2.03	0.00	0.00
Class VI (1320)																
Low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low-intermediate	305.70	13.65	206.24	9.99	75.92	12.21	0.00	0.00	0.00	0.00	160.31	16.54	0.48	0.27	0.00	0.00
Intermediate	741.56	33.12	731.72	35.46	217.38	34.96	0.00	0.00	0.00	0.00	283.92	29.30	56.00	31.22	0.00	0.00
High-intermediate	1,163.50	51.96	994.85	48.21	309.42	49.76	0.00	0.00	0.00	0.00	466.90	48.18	115.89	64.61	0.00	0.00
High	28.39	1.27	130.98	6.35	19.09	3.07	0.00	0.00	0.00	0.00	57.96	5.98	6.99	3.89	0.00	0.00
Area/ of region	2,239.14	35.26	2,063.79	32.04	621.81	9.88	0.00	0.00	0.00	0.00	969.09	15.07	179.36	2.86	0.00	0.00
Class VII (1380)																
Low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low-intermediate	504.43	18.87	214.54	11.44	431.95	26.23	0.00	0.00	0.00	0.00	483.54	18.40	270.06	21.23	0.00	0.00
Intermediate	1,162.51	43.49	691.46	36.87	584.81	35.52	12.98	60.32	0.00	0.00	1,054.50	40.14	370.39	29.11	4.38	25.70
High-intermediate	967.73	36.20	919.04	49.00	604.58	36.72	8.54	39.68	0.00	0.00	1,036.86	39.46	508.60	39.98	12.65	74.30
High	38.27	1.43	50.61	2.70	25.30	1.54	0.00	0.00	0.00	0.00	52.45	2.00	123.14	9.68	0.00	0.00
Area/ of region	2,672.93	42.09	1,875.65	29.12	1,646.63	26.16	21.52	0.36	0.00	0.00	2,627.34	40.84	1,272.20	20.26	17.03	0.28
Class VIII (1440)																
Low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low-intermediate	193.06	20.87	140.71	24.62	380.76	15.35	267.08	22.44	0.00	0.00	391.50	21.90	994.66	24.38	247.02	26.25
Intermediate	418.34	45.23	336.74	58.91	1,140.79	45.98	453.19	38.08	0.00	0.00	778.97	43.57	1,878.42	46.04	359.88	38.25
High-intermediate	313.46	33.89	93.89	16.43	955.35	38.50	462.81	38.89	0.00	0.00	615.28	34.41	1,199.82	29.41	319.20	33.93
High	0.00	0.00	0.24	0.04	4.41	0.18	6.92	0.58	0.00	0.00	2.09	0.12	6.82	0.17	14.78	1.57
Area/ of region	924.86	14.56	571.58	8.87	2,481.31	39.43	1,189.99	19.72	0.00	0.00	1,787.85	27.79	4,079.72	64.96	940.87	15.31
Class IX (>1500)																
Low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low-intermediate	0.00	0.00	85.81	38.05	496.27	33.80	1,306.90	27.09	1,578.52	26.12	193.54	28.11	178.28	31.06	1,307.28	25.20
Intermediate	0.00	0.00	125.32	55.57	791.18	53.88	2,340.41	48.52	2,808.47	46.47	411.11	59.72	370.05	64.47	2,466.14	47.54
High-intermediate	0.00	0.00	14.40	6.39	180.91	12.32	1,175.26	24.36	1,648.32	27.27	83.81	12.17	25.65	4.47	1,403.90	27.06
High	0.00	0.00	0.00	0.00	0.00	0.00	1.13	0.02	8.05	0.13	0.00	0.00	0.00	0.00	9.97	0.19
Area/ of region	0.00	0.00	225.53	3.50	1,468.36	23.33	4,823.70	79.93	6,043.36	100.00	688.46	10.70	573.99	9.14	5,187.30	84.41

consistent with Webb, Whetton, and Barlow (2007) and Hall and Jones (2008), suggesting that harvests are likely to occur earlier and seasons will be shortened due to warming. Additionally, within this study the analysis of irrigation need and heat risk does suggest that the future capacity of Maipo Valley vineyards to produce high-quality grape varietals from intermediate climate maturity classes (including Cabernet Sauvignon) could be limited.

Jones (2005) found that many grape-growing regions are at, or near, their optimal growing season temperature. The baseline assessment of grape variety maturity classes within the Maipo Valley suggests that the same situation exists within the study area where the premium cultivars Cabernet Sauvignon (Class VI), Carmenére (Class VII), and Merlot (Class V) are grown in areas with growing season heat accumulation that are close to ideal for their corresponding climate maturity class. Vineyard managers might be able to adapt to some of these climatic shifts through the employment of adaptive management strategies, the utilization of varietals suited to warmer climates, and the establishment of vineyards at higher elevation sites. Fraga et al. (2012) suggested that adaptation strategies within viticulture can be focused on short-term impacts by addressing specific threats through crop management practices or longer term impacts through varietal and land allocation changes.

In addition to the progressively higher average temperatures modeled for this region, a significant increase in the occurrence of extreme heat events could have an impact on the viticultural suitability of this valley. Temperatures above 30°C have been found to reduce berry size and weight (Hale and Buttrose 1974) and stop metabolic processes and sugar accumulation altogether (Kriedemann and Smart 1971; Coombe 1987). Hall and Jones (2010) found that BEDD as a suitability index produces actual daily mean temperatures closer to reality, although due to its 9°C cap it is less sensitive to large increases in temperature. Our inclusion of extreme heat as a suitability variable allowed us to capture large temperature increases as well as retain a robust index for characterizing viticultural suitability. An increase in the frequency and severity of extreme heat events could adversely affect the quality of grapes produced in Maipo Valley, increasing the risk associated with cultivation.

A climatic factor not incorporated into this study is the potential impact of climate change on precipitation within this region. The majority of vineyards within Maipo Valley are irrigated, mitigating acute drought impacts on vines. Meza et al. (2012) projected that precipitation levels will decrease in the Maipo Basin by the end of the century and irrigation needs will likely increase, causing increased stress on water resources. The issue of water scarcity within the Maipo, which is currently in the midst of a prolonged drought, will become increasingly important as a resource constraint for viticulturalists and other agricultural users within the Maipo River basin.

This study has been constrained by the relatively limited temperature records available for Maipo Valley. Many records are limited in timescale when compared to temperature data records available in other wine-growing regions internationally. Because historic temperature data are used to downscale GCMs, this lack of data availability reduces the resolution of these models. Additionally, regression-based statistical downscaling has been found to increase the uncertainty of the constituent global circulation models and greenhouse gas emissions that comprise them. Chen, Brissette, and Leconte (2011) suggested that climate change impact studies should include more than one downscaling method to better represent the uncertainty inherent within downscaling. Within this study, we chose climate change models that were best suited to the Southern Cone to increase the robustness of our findings as well as downscaling methodology that was well suited to our research objectives (Hayhoe et al. 2004; Wood et al. 2004; Maurer and Duffy 2005; Maurer et al. 2007). To further improve our analysis, a future productive avenue of study would be to use additional downscaling methodologies in modeling climate change impacts on viticulture within the Maipo Valley to better quantify uncertainty within our analysis.

Conclusion

This study used topographic, soil, land use, and historical climate data to analyze the baseline viticultural suitability of the Maipo Valley in Central Chile. Historical data were then used to downscale GCMs for scenario A1b and B1 for three thirty-year normals spanning from 2010 to 2100. These projected climate data were used to analyze projected viticultural suitability. The results of this study indicate that there is a significant trend toward hotter climate maturity classes within Maipo Valley. This suggests that the capacity of wine producers to cultivate high-quality grapes from traditional varietals could become increasingly limited if no adaptation measures are taken. This research opens new opportunities for comparative regionally focused studies, providing a broader understanding of the commonalities and differences in climate change impacts on the viticultural suitability of prominent wine-growing regions internationally. Additionally, despite the inherent uncertainty in climate change analyses such as this one, studies of this nature reinforce the importance of investing in research relating to adaptive vineyard management practices and resilient varietals.

Acknowledgments

The authors appreciate the contribution of David Poblete and Eduardo Bustos from the Centro de Cambio Global for their help with the downscaling process and troubleshooting, as well as Anna and Zack

Steel for assistance with programming and cartography, respectively. Thanks also go to the Fulbright Commission-Chile for their support of this work. Finally, the authors would like to thank the UA SGD's Writing Workshop peer group for their guidance and support.

Funding

This work was partially supported by Fondecyt Grant 1120713 during the analysis stage and by the Inter-American Institute for Global Change Research (IAI, project CRN3056, which is supported by U.S. National Science Foundation grant GEO-1128040).

Literature Cited

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration—Guidelines for computing crop water requirements. Food and Agriculture Organization Irrigation and Drainage Paper 56, Food and Agriculture Organization, Rome, Italy.

Cass, A. 1999. What soil factors really determine water availability vine? *Australian Grapegrower and Winemaker Annual Technical Issue* 426a:95–97.

Cass, A., D. Hansen, and A. Dowley. 2002. Grape performance and soil conditions. In *Sustainable viticulture production: Optimizing soil resources*, ed. A. Cass, 5–15. Adelaide, AU: CSIRO Land and Water.

Chen, J., F. P. Brissette, and R. Leconte. 2011. Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. *Journal of Hydrology* 401:190–202.

Coombe, B. G. 1987. Influence of temperature on composition and quality of grapes. *Proceedings of the Symposium on Grapevine Canopy and Vigour Management. Acta Horticulturae* 206:23–35.

Dry, P. R., and R. E. Smart. 1988. Vineyard site selection. In *Viticulture*, ed. B. G. Coomber and P. R. Dry, 190–204. Adelaide, Australia: Winetitles.

Fraga, H., A. C. Malheiro, J. Moutinho-Pereira, and J. A. Santos. 2012. An overview of climate change impacts on European viticulture. *Food and Energy Security* 1 (2): 94–110.

Garreaud, R. D., and M. Falvey. 2009. The coastal winds off western subtropical South America in future scenarios. *International Journal of Climatology* 29 (4): 543–54.

Gil, G., and P. Pszczólkowski. 2015. *Viticultura: Fundamentos para optimar producción y calidad* [Viticulture: Fundamentals to optimize production and quality]. Santiago, CL: Catholic University Press of Chile.

Gladstones, J. 1992. *Viticulture and environment*. Adelaide, Australia: Winetitles.

———. 2011. *Wine, terroir and climate change*. Kent Town, Australia: Wakefield Press.

Hale, C. R., and M. S. Buttrose. 1974. Effect of temperature on ontogeny of berries of Vitisvinifera L. cv. Cabernet Sauvignon. *Journal of the American Society of Horticultural Science* 99:390–94.

Hall, A., and G. V. Jones. 2008. Effect of potential atmospheric warming on temperature-based indices describing Australian winegrape growing conditions. *Australian Journal of Grape and Wine Research* 15 (2): 97–119.

———. 2010. Spatial analysis of climate in winegrape-growing regions in Australia. *Australian Journal of Grape Wine Research* 16:389–404.

Hannah, L., P. Roehrdanz, M. Ikegami, A. V. Shepherd, M. R. Shaw, G. Tabor, L. Xhi, P. Marquet, and R. Hijmans. 2013. Climate change, wine, and conservation. *Proceedings of the National Academy of Sciences* 110 (17): 6907–12.

Hayhoe, K., D. Cayan, C. B. Field, P. C. Frumhoff, E. P. Maurer, N. L. Miller, S. C. Moser, et al. 2004. Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences* 101 (12): 422–27.

Huglin, P. 1978. Nouveau mode d'evaluation des possibilities héliothermiques d'unmilieu viticole [New methods for evaluation of thermal solar for viticulture]. *Comptes rendus de l'académie d'agriculture de France* 64:1117–26.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Emission scenarios: Special report on emissions scenarios*, ed. N. Nakicenovic and R. Swart. Cambridge, UK: Cambridge University Press.

———. 2007. *Climate change 2007: The physical science basis*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. Cambridge, UK: Cambridge University Press.

———. 2014. *Climate change 2014: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. C. B. Field, V. R. Baroos, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, et al. Cambridge, UK: Cambridge University Press.

Jones, G. V. 2005. Climate change and global wine quality. *Climatic Change* 73 (3): 319–43.

———. 2006. Climate change and wine: Observations, impacts and future implications. *Wine Industry Journal* 21 (4): 21–26.

———. 2007. Climate change and the global wine industry. *Proceedings of the 13th Australian Wine Industry Technical Conference*, 1–8, Adelaide, AU.

Jones, G. V., N. Sneed, and P. Nelson. 2004. Modelling viticultural landscapes: A GIS analysis of the terroir potential in the Umpqua Valley of Oregon. *Geoscience Canada* 31 (4): 167–78.

Keller, M. 2010. Managing grapevines to optimise fruit development in a challenging environment: A climate change primer for viticulturalists. *Australian Journal of Grape and Wine Research* 16:56–69.

Knutti, R., and J. Sedlacek. 2013. Robustness and uncertainities in the new CMIP5 climate model projects. *Nature Climate Change* 3:369–73.

Koufos, G., T. Mavromatis, S. Koundouras, N. Fyllas, and G. Jones. 2014. Viticulture-climate relationships in Greece: The impacts of recent climate trends on harvest date variation. *International Journal of Climatology* 34:1445–59.

Kriedemann, P. E., and R. E. Smart. 1971. Effects of irradiance, temperature and leaf water potential on photosynthesis of vine leaves. *Photosynthetica* 6:6–15.

Marengo, J. A., R. Jones, L. M. Alves, and M. C. Valverde. 2009. Future changes of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modelling system. *International Journal of Climatology* 29 (15): 2241–55.

Margarey, R. D., R. C. Seem, and S. D. DeGloria. 1998. Prediction of vineyard site suitability. *Grape Research News* 9 (1): 1–2.

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy. 2007. Fine-resolution climate change projections enhance regional climate change impact studies. *Eos: Transactions of the American Geophysical Union* 88:504.

Maurer, E. P., and P. B. Duffy. 2005. Uncertainty in projections of stream-flow changes due to climate change in California. *Geophysical Research Letters* 32:L03704.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, et al. 2007. Global climate projections. In *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, 747–846. Cambridge, UK: Cambridge University Press.

Meza, F., D. S. Wilks, L. Gurovich, and N. Bambach. 2012. Impacts of climate change on irrigated agriculture in Maipo Basin, Chile: Reliability of water rights and changes in the demand for irrigation. *Journal of Water Resource Planning and Management* 138:421–30.

Montes, C., J. F. Perez-Quezada, A. Peña-Neira, and J. Tonietto. 2012. Climatic potential for viticulture in central Chile. *Australian Journal of Grape and Wine Research* 18 (1): 20–28.

Moriondo, M., G. V. Jones, B. Bois, C. Dibari, R. Ferrise, G. Trombi, and M. Bindi. 2013. Projected shifts of wine regions in response to climate change. *Climatic Change* 199:825–39.

Panofsky, H. A., and G. W. Brier. 1968. *Some applications of statistics to meteorology*. University Park: Pennsylvania State University.

Rosenbluth, B., G. Casassa, and H. Fuenzalida. 1997. Recent temperature variations in southern South America. *International Journal of Climatology* 17:67–85.

Seguin, B., and I. G. De Cortazar. 2005. Climate warming: Consequences for viticulture and the notion of "terroirs" in Europe. *Acta Horticulturae* 689 (1): 61–69.

Servicio Agrícola y Ganadero (SAG). 2011. Servicio Agrícola y Ganadero vineyard registry. http://www.sag.cl/ambitos-de-accion/catastro-viticola (last accessed 24 March 2015).

———. 2013. Servicio Agrícola y Ganadero vineyard registry. http://www.sag.cl/ambitos-de-accion/catastro-viticola (last accessed 24 March 2015).

———. 2014. Servicio Agrícola y Ganadero vineyard registry. http://www.sag.cl/ambitos-de-accion/catastro-viticola (last accessed 24 March 2015).

Tonietto, J., and A. Carbonneau. 2004. A multicriteria climatic classification system for grape growing regions worldwide. *Agricultural and Forest Meteorology* 124: 81–97.

Vadour, E. 2002. The quality of grapes and wine in relation to geography: Notions of terroir at various scales. *Journal of Wine Research* 12 (2): 95–109.

Webb, L. B., P. H. Whetton, and E. W. R. Barlow. 2007. Modeled impact of future climate change on the phenology of winegrapes in Australia. *Australian Journal of Grape Wine Research* 13:165–75.

White, M. A., N. S. Diffenbaugh, G. V. Jones, J. S. Pal, and F. Giorgi. 2006. Extreme heat reduces and shifts United States premium wine production in the 21st century. *Proceedings of the National Academy of Sciences* 103 (30): 11217–22.

Winkler, A. J., J. A. Cook, W. M. Kliewer, and L. A. Lider. 1974. *General viticulture*. Berkeley: University of California Press.

Wood, A. W., L. R. Leung, V. Sridhar, and D. P. Lettenmaier. 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. *Climatic Change* 62:189–216.

MEGAN MILLS-NOVOA is a graduate student in the School of Geography and Development at the University of Arizona, Tucson, AZ 85721. E-mail: mmillsnovoa@email.arizona.edu. Her research interests include Andean agricultural systems, climate change adaptation, and mixed-method approaches.

PHILIPPO PSZCZÓLKOWSKI is a Professor of enology in the Facultad de Agronomia e Ingeniería Forestal at the Pontificia Universidad Católica de Chile, Santiago, 7820436, Chile. E-mail: philippo@uc.cl. His research interests include Chilean viticulture and enology.

FRANCISCO MEZA is a Professor in the Departamento de Ecosistemas y Medio Ambiente in the Facultad de Agronomia e Ingeniería Forestal and the Director of the Centro de Cambio Global at the Pontificia Universidad Católica de Chile, Santiago, 7820436, Chile. E-mail: fmeza@uc.cl. His research interests include impacts of global change on agriculture, forest and water resources and the development of adaptation strategies for these sectors.