

Projecting future winegrape yields using a combination of *Vitis vinifera* L. growth rings and soil moisture simulations, northern California, USA

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Abstract

Background and Aim: We examined the feasibility of projecting future winegrape productivity by using *Vitis vinifera* L. growth rings as a proxy to winegrape yields.

Methods and Results: We compared the climate response of *V. vinifera* radial growth rings and winegrape yields using DENDROCLIM2002. We used the soil moisture model HYDRUS to determine if *V. vinifera* radial growth rings and winegrape yield can be modelled by soil moisture. Changes in *V. vinifera* radial growth were projected for 2020/99 Common Era using downscaled general climate models. Climate influences *V. vinifera* radial growth and winegrape yield similarly ($r = 0.53$, $P = 0.001$), indicating that *V. vinifera* can be used as a proxy for winegrape yield. Additionally, HYDRUS provided a robust model for vine growth and winegrape yield. Projected yields are forecasted to decrease significantly through time.

Conclusions: Based on future climate, winegrape yield showed a consistent and significant decreasing trend resulting in a 12.4% decrease by 2099.

Significance of the Study: Future climate conditions could create a decreasing trend in future winegrape yields, indicating that developing new irrigation systems or increasing irrigation volume will possibly be required for continued winegrape production in California.

Keywords: agriculture, climate change, dendrochronology, HYDRUS, viticulture

Introduction

Background

The California wine industry has a \$52 billion impact on the state economy and a \$125 billion impact on the US economy (MFK Research 2007). Climate is the dominant control on the production of winegrapes, with changes in climate and variability influencing winegrape yield and composition (Jones et al. 2005, 2012, Webb et al. 2007, 2008, Ramos et al. 2008, Santos et al. 2011). Thus, information on how a changing climate will influence grapevine growth and winegrape yield can be used to understand better the best adaptation methods during this period of impending climate change.

Changes in climatic conditions are predicted to influence winegrape productivity in complex ways in the near future (Jones et al. 2005, Jones and Goodrich 2008). In many regions, warming temperature, especially increases in nighttime lows, has shown to positively influence winegrape yield and composition (Nemani et al. 2001, Jones et al. 2005). The ideal temperature limit of grapevines, however, could be exceeded with continued warming, and thus requires adaptation by growers for continued yield sustainability, including increasing irrigation, changing cultivars or even relocating to new regions (Jones 2007, Jones and Goodrich 2008).

While much is known about how changing climatic conditions have altered some aspects of wine production, little is known about the potential impact to long-term grapevine growth characteristics. Short-term growth characteristics have been captured in grapevine phenology, which has been documented to be sensitive to climate change, with budburst occurring 2–5 days earlier per decade over the last 25–35 years, depending on cultivar and region (Seguin and de Cortazar 2005, Wolfe et al. 2005, Jones 2007, Tomasi et al. 2011). Similarly, earlier grape ripeness dates have been documented in many wine regions of the world (Jones 2007, Webb et al. 2011) and is being attributed to increasing temperature and drying soil moisture (Webb et al. 2012). Increasing temperature is predicted to continue to influence grapevine phenology until growth thresholds are exceeded, adversely affecting overall winegrape quantity and composition (Webb et al. 2007). The impact, however, of projected warming in the scientific literature is only based on grapevine threshold temperature. Little is known about how changes in climate could impact the radial growth of grapevine stems in the future. Further, no studies have examined if observed climate change has already had an influence on grapevine radial stem growth.

The radial growth of woody plant species is often related to previous- and/or current-year environmental variability, such as climate, hydrology, carbon storage, mast production and natural/

anthropogenic disturbance (Fritts 1976). Therefore, we postulate that techniques of dendrochronology (tree-ring science) could be used to provide information on the growth dynamics of *V. vinifera* as related to climate variability and fruit production. Thus, growth rings between individuals of *V. vinifera* used in wine production should also respond similarly to climate variability. We further reasoned that climate variability would influence winegrape yield in a similar fashion, and thus *V. vinifera* radial growth rings would relate to winegrape yield. Using growth rings as a proxy for agricultural production has been successful for reconstructing corn and bean yields (Burns 1983), maize yields (Therrell et al. 2006) and tupelo honey – a specialty honey derived from nectar from *Nyssa ogeche* Bartr. in the USA (Maxwell and Knapp 2012, Maxwell et al. 2013). No studies, however, have used growth rings for winegrapes as a proxy to project yields into the future. Tyminski (2013) found that growth rings of *V. vinifera* from a wooded area in North Carolina, USA, responded similarly to climate and indicated that using growth rings as a proxy to grape yield may be possible from vines in wine production. Changes in the methods of reporting winegrape yields through time (e.g. changes in the reporting districts in California) make examining trends in grape yield through time difficult. For example, the reporting District 1 in California included both Mendocino and Lake Counties from 1976 to 1978, but only included Mendocino County post-1978. The change in recording methodologies can introduce inaccuracies when comparing data through time. Thus, using *V. vinifera* growth as a proxy of historical yield can provide a better method to examine historical trends in winegrape yield as the growth of the vine is not susceptible to changes in reporting methodologies.

By establishing the climate response of *V. vinifera* growth and the influence of climate variability on winegrape yield, we postulated that both would correlate to soil moisture simulated using the HYDRUS soil water numerical model package, allowing us to project the impact of future climate change on both growth and yield. Thus, the overall objective of this project was to examine the feasibility of projecting future winegrape yield using *V. vinifera* growth as a proxy. Specifically, we (i) examined and compared the climate response of *V. vinifera* radial growth rings and winegrape yield; (ii) determined if *V. vinifera* radial growth rings and winegrape yield can be modelled by soil moisture; and (iii) projected changes in *V. vinifera* radial growth from future climate change using downscaled general climate models (GCMs), and the documented relationship between soil moisture and *V. vinifera* growth as a proxy of future winegrape yield.

Materials and methods

Sample collection and preparation

We acquired nine cross-sections of *V. vinifera* (cv. Zinfandel) from the Pacini Vineyard (Ukiah, Mendocino County, CA, USA) within the North Coast American Viticultural Area (NCAVA) (Figure 1). At just over 1.2 million hectares of total land and 18 000 hectares of vineyards planted, the North Coast is one of the largest American Viticultural Areas in California, one of the largest wine-producing regions in the USA (Jones et al. 2010), and attracts millions of tourists every year. Located in northern California, the NCAVA includes Lake, Marin, Mendocino, Napa, Solano and Sonoma counties (Figure 1). Beginning in the mid-19th century, the NCAVA includes about 800 wineries, almost half of the state's wineries. The NCAVA has a long growing season with warm days and cool evenings and enough precipitation that allows many vineyards to grow without irrigation (depending on location), making it an ideal climate for wine production.



Figure 1. A map of the study site (●) within the North Coast American Viticultural Area (NCAVA) (▭) and California (▭) and the surrounding HYDRUS sites (▲). CA 1 represents California Climate Division 1.

The region encompassing the site has a warm growing season, with an average temperature during the harvesting season of 17°C. The annual average precipitation of 960 mm typically occurs during the winter months, making growing season drought a potential hazard for *V. vinifera* growth and winegrape yield. The vineyard where the samples were obtained is not irrigated, making it an ideal location to examine potential linkages between *V. vinifera* growth, winegrape yield and soil moisture.

The cross-sections were dried, mounted and sanded to a high polish. Samples were then ring-counted, visually cross-dated using the list method (Yamaguchi 1991), and then all rings were measured to the nearest 0.001 mm accuracy using a Velmex measuring stage coupled with the MEASURE J2X software (Voorhees 2000). To ensure cross-dating accuracy, we statistically verified the ring-width measurements with the computer program COFECHA (Holmes 1983), which uses segmented time series correlation techniques to ensure that a growth ring is statistically assigned an accurate calendar year (Grissino-Mayer 2001). To remove biological growth trends, we used the program ARSTAN (Cook 1985) and applied either a negative exponential or negative linear detrending line to each measurement series.

Data

We acquired data on the tonnes of grapes crushed (hereafter 'yield') for California Grape Pricing District 1 (Mendocino County) from the California Department of Food and Agriculture (NASS 2012) during the period 1976/2012 Common Era, which is the common period between the grape yield data and the *V. vinifera* chronology. California Grape Pricing District 1 included Lake County as well from 1976 to 1978, and created some slight inconsistencies in the methodologies for reporting yield. Further, grapes purchased and then crushed are included in this dataset, which could potentially mask the overall yield crushed. This

dataset, however, is one of the longest recorded that reports data at a higher resolution than that at the state level (grape pricing districts). Long-term yield data at the vineyard level were not available. Grape yield has increased through time because of numerous advances, such as the influence of improvements in technology and more vineyards planted; thus, we fitted a linear line to the yields and took the residuals (see Table S1 for raw and standardised values). A variety of climatic variables were selected to examine influences on *V. vinifera* growth and winegrape yield. These variables were obtained for California Climate Division 1 (North Coast Drainage) from the National Climatic Data Center, and include monthly mean temperature, total monthly precipitation and Palmer Drought Severity Index (PDSI; Palmer 1965) during the period 1895–2012.

Grapevine growth and grape climate models

We used correlation function analysis to examine how regional climatic variables (monthly mean temperature, total monthly precipitation and PDSI) influence *V. vinifera* growth using the program DENDROCLIM2002 (Biondi and Waikul 2004). The program uses bootstrapping to yield more accurate confidence levels, determines significance at the 95% confidence level and removes autocorrelation of climatic variables (Biondi 1997, Biondi and Waikul 2004). The correlation function analysis produces coefficients that are univariate estimates of Pearson's product-moment correlation (Biondi and Waikul 2004). Correlation coefficients were calculated with bootstrapped confidence intervals to reduce potential error and obtain more accurate results (Biondi 1997). We conducted these analyses using climate variables covering a 23-month period (February of the previous year to December of the current year of radial growth) for the entire length of the chronology. This period was selected because conditions during the previous and current year growing season can affect the amount of carbon fixed and allocated to growth (Fritts 1976), and especially grapevines where the current year buds, and therefore fruitfulness, are set during the previous year (Mullins et al. 1992).

To determine the climatic mechanisms behind grape yield variability, we used an identical analysis to the *V. vinifera* climate response, except the US Department of Agriculture grape yield data were analysed in place of the *V. vinifera* annual radial growth time series for the period of data recording (1976–2012). This analysis allows us to compare how differently or similarly the *V. vinifera* growth and grape yield records respond to the climate variables, which facilitates a better understanding of the relationship between *V. vinifera* growth and grape yield. The PDSI was a significant climate variable for both *V. vinifera* growth and grape yield, and thus justifies examining the relationship of both with the HYDRUS model. After comparing the climate responses for *V. vinifera* growth and winegrape yield, we correlated the growth chronology with winegrape yield to determine if the *V. vinifera* growth could be used as a proxy to yield.

Description of HYDRUS

The numerical model package HYDRUS (Šimůnek et al. 2005) was used to simulate soil water flow, vine root water uptake, and soil water evaporation in a one-dimensional, variably saturated soil media. HYDRUS approximates the solution to the Richards equation, the governing equation of water flow:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[K \left(\frac{\partial h}{\partial x} + 1 \right) \right] - S \quad (1)$$

where θ is the volumetric soil water content, t is time, h is the water pressure head, x is the spatial coordinate, and K is the

unsaturated hydraulic conductivity, a function of the saturated hydraulic conductivity (K_s) and water content. S is a sink term that accounts for the uptake of soil water by vegetation (Feddes et al. 1978):

$$S(h) = \alpha(h) S_p \quad (2)$$

where $S(h)$ is the water uptake rate, $\alpha(h)$ is a water stress response function ($0 \leq \alpha \leq 1$) that describes the reduction in uptake under stressed conditions (Feddes et al. 1978), and S_p is the potential water uptake rate and is a function of potential evapotranspiration. The values for $\alpha(h)$ are crop-specific, and the vineyard values were extracted from the database contained within HYDRUS (Šimůnek et al. 2005). The van Genuchten (1980) and Mualem (1976) representations for unsaturated hydraulic properties were used to determine soil hydraulic properties. The HYDRUS model for this study used physical soil properties extracted from the Soil Survey Geographic database (SSURGO) for the vineyard location (Figure 1). No soil water data were available for a specific site calibration, and therefore HYDRUS was not calibrated to present conditions.

To assess the reliability of HYDRUS to accurately simulate soil moisture with uncalibrated parameters, four HYDRUS models were created throughout California, and their results were compared against monthly observed soil moisture data obtained from AmeriFlux (<http://ameriflux.ornl.gov/>) and the National Oceanic and Atmospheric Administration Hydrometeorology Testbed (<http://hmt.noaa.gov/>). The locations of these sites in California are near Blodgett, Healdsburg and two sites near Ione (Figure 1). For the Blodgett site, at a depth of 30 cm and 50 cm, HYDRUS accurately estimated soil moisture content compared with observed data with R^2 values of 0.88 and 0.87, root mean square errors of 2.9 and 2.7%, and per cent bias values of -2 and -1.6% , respectively. For the Healdsburg location at a depth of 10 cm, a R^2 value of 0.85 was found, along with a 7% root mean square error and a per cent bias of -0.3% . For the two sites near Ione, we obtained R^2 values of 0.75 and 0.76, root mean square errors of 6.2 and 6.6%, and per cent bias values of 13 and -4% as compared with observed data. Therefore, from this preliminary work, we can assume that HYDRUS adequately estimates soil moisture based on default soil types and climate data.

Downscaled climate projections

Downscaled climatic projections at a 12-km resolution from seven GCMs (Table 1) and one Intergovernmental Panel on Climate Change representative concentration pathway [8.5 (high emissions); RCP] from 2020/99 were used as climatic inputs to the HYDRUS model. With multiple GCM projections, a quantitative assessment of the spread of the projections around the mean can be performed, providing an idea of the projection uncertainty (Meehl et al. 2007). Only one RCP, intended to be the most 'pessimistic' concentration pathway, was considered for this study. Using the most pessimistic scenario allowed us to gather results regarding a worst-case scenario. All downscaled GCM output was extracted from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections web site [[http://gdo-dcp.ucllnl.org](http://gdo-dcp.ucllnl.org;); Maurer et al. (2014)] for the nearest latitude/longitude to the vineyard (39.0625 °N, -123.1875 °W). The original GCM data were extracted from the World Climate Research Programme's Coupled Model Intercomparison Project phase 5 (CMIP5; Taylor et al. 2012) and interpolated to a 2° grid, which was then statistically downscaled using the bias correction and spatial disaggregation method of Wood et al. (2004). This disaggregation method has been widely used throughout

Table 1. Description of climate models used.

Modelling group	Climate model ID	Reference
Canadian Centre for Climate Modelling and Analysis	CanESM2	Chylek et al. (2011)
Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5	Voldoire et al. (2013)
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-CM3	Donner et al. (2011)
Institut Pierre-Simon Laplace	IPSL-CM5A-LR	Dufresne et al. (2013)
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM	Watanabe et al. (2011)
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-ESM-LR	Giorgetta et al. (2013)
Meteorological Research Institute	MRI-CGCM3	Yukimoto et al. (2012)

the western USA (e.g. Hayhoe et al. 2004, Maurer 2007, Ficklin et al. 2013). The CMIP5 model output is monthly precipitation and monthly average maximum and minimum temperature from 1950 to 2099. For this work, however, we used the time range of 2020/99. These data were input into the HYDRUS model. We used the Mann-Kendall test to determine if the observed and projected winegrape yield contained significant ($P < 0.05$) trends, and the Rodionov (2004) algorithm to examine if potential significant ($P < 0.05$) regime shifts were present.

Results and discussion

Cross-dating statistics

We visually and statistically cross-dated all nine samples taken from the Pacini Vineyard and were successful in developing a *V. vinifera* growth ring chronology that spans from 1972 to 2012. Cross-dating is the defining technique of the science of dendrochronology and is a method of visually and statistically matching patterns of wide and narrow growth rings between individual trees, or in our case vine stems. Using the program COFECHA, we found a significant interseries correlation ($r = 0.43$; $P < 0.001$) and high average mean sensitivity (0.34) of our *V. vinifera* chronology. High interseries correlations indicate that the samples have similar temporal variability in ring width. Average mean sensitivity is a measure of interannual variability of ring width, with a higher sensitivity corresponding to species for which annual growth is sensitive to environmental or climatic conditions. Both the interseries correlation and the average mean sensitivity values are comparable to values derived from tree species used to reconstruct climate (International Tree Ring Data Base 2014).

Climate analysis of grapevine growth and grape yield

The correlation analysis between the chronology and mean annual temperature, total mean precipitation, and mean annual PDSI from California Climate Division 1 revealed that *V. vinifera* contained a distinct climate signature. Grapevine growth was positively correlated with the previous autumn temperature (September) and negatively correlated with current-year late spring and late summer temperature (April and August; Figure 2a). Spring rainfall was also important for *V. vinifera* growth, as vines were positively correlated with precipitation during previous-year May and June and current-year March and April. Moreover, we discovered a strong drought signal in *V. vinifera*, as vines were strongly positively correlated with previous summer PDSI and current-year spring PDSI.

The climate analysis of winegrape yield and *V. vinifera* growth revealed a similar pattern during the current growth

year; however, only *V. vinifera* had a relationship to previous-year climate conditions (Figure 2). Temperature was significantly related to winegrape yield during the previous-year July (positive influence) and current-year August (negative influence). While overall yield and vine growth responded to a similar seasonal temperature, the monthly temperature response differed the most compared with the other climate variables. Rainfall and soil moisture (i.e. PDSI) showed more similar patterns between yield and vine growth, with current-year March and April significantly influencing both winegrape yield and vine growth. There were, however, some small differences with winegrape yield responding to October precipitation and January soil moisture when vine growth did not. Additionally, *V. vinifera* growth had a strong previous year relationship, especially with soil moisture, while winegrape yield did not exhibit any lagged influence from the moisture variables (i.e. precipitation and PDSI). While differences in the climate responses between vine growth and yield exist, they both had the strongest correlation with spring (March and April) precipitation and soil moisture, indicating that climate may potentially influence both in a similar fashion.

Growth and yield relationship

We found a significant correlation ($r = 0.53$, $P = 0.001$) between the *V. vinifera* growth ring chronology and winegrape yield, indicating that future climate change will likely have a comparable impact on winegrape yield as it does on *V. vinifera* growth (Figure 3). We posit that when conditions are conducive to vine growth, grapevines can also allocate resources to grape production, and thus winegrape yield responds positively to favourable growth conditions. The climate response in Figure 2 confirms that both grape production and vine growth are responding to similar climatic conditions. The significant correlation and similar climate response indicates that *V. vinifera* growth rings can be used as a proxy for grape yield. This relationship was established from growth rings from one vineyard and compared with a regional value of grape yield. The regional yield data come from a variety of vineyards that use different management practices (e.g. irrigation). Site-specific yield data would likely improve the correlation as to allow for a more accurate comparison to vine growth. Many yield records, however, are either not readily available or are short in nature and make statistical comparisons difficult. Similarly, samples from multiple vineyards around the region could also improve the relationship between growth and yield by better encompassing the regional variability in climate. Our results show initial promise for the utility of using *V. vinifera* growth rings as a proxy of winegrape yields. Further, because vines are not susceptible to changes in reporting methodologies, they provide another metric to be used when combining yield reports through time. Last, with

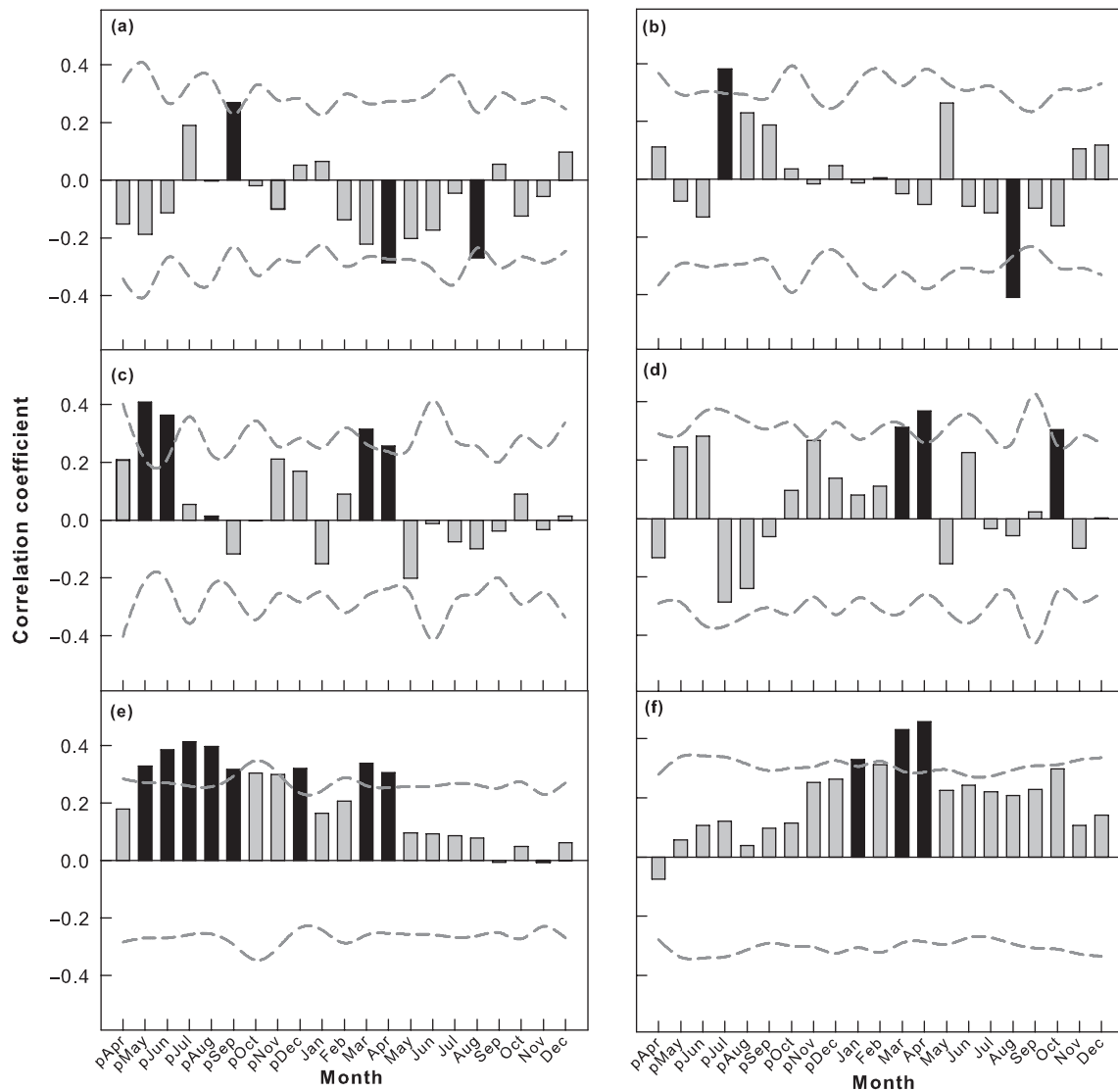


Figure 2. Correlation analysis of climate data [(a,b) mean monthly temperature, (c,d) total monthly precipitation and (e,f) mean monthly Palmer Drought Severity Index (PDSI)] from California Climate Division 1 for the period 1972–2012 compared with (a,c,e) *Vitis vinifera* chronology and (b,d,f) tonnes of grapes crushed for Mendocino County from the California Department of Food and Agriculture. Dashed lines indicate the $P < 0.05$ significance level for the correlations.

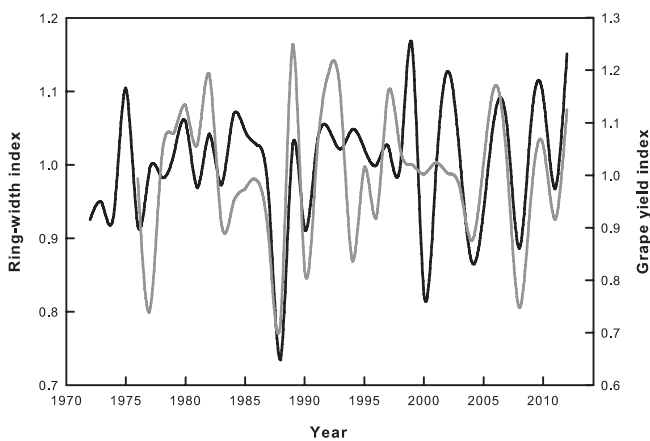


Figure 3. Annual change in winegrape yield and vine growth is significantly correlated ($r = 0.53$; $P < 0.001$). Standardised *Vitis vinifera* chronology index (—) was developed from samples at the Pacini Vineyard (Ukiah, CA, USA) in the heart of the North Coast American Viticultural Area. Grape yield (---) is the standardised index of total annual crushed wine cultivar grapes for Mendocino County, California (data source: NASS 2012).

older vines available to sample, our results show promise of a potential reconstruction of yields using vine stems.

Growth and yield relationship with HYDRUS results

Correlations were also assessed between HYDRUS-simulated soil moisture at the Pacini Vineyard location (Figure 1) and the *V. vinifera* growth ring chronology from vine stems from the site. The results reveal a significant correlation ($r = 0.54$, $P < 0.001$) between *V. vinifera* growth ring chronology and HYDRUS-simulated soil moisture. The multiple regression model included soil moisture simulated at depths of 10, 20 and 30 cm, total summer precipitation, and annual average air temperature as independent variables, and *V. vinifera* growth ring chronology as the dependent variable. The R^2 and per cent bias for the *V. vinifera* growth ring chronology model and the observed *V. vinifera* growth ring chronology was 0.29 and ca. 0.00%, respectively. These results support the use of the HYDRUS model to project further *V. vinifera* growth based on future climatic conditions from an ensemble of GCMs. Further, because winegrape yield and *V. vinifera* growth correlate, these projections can be used as a proxy for winegrape yield.

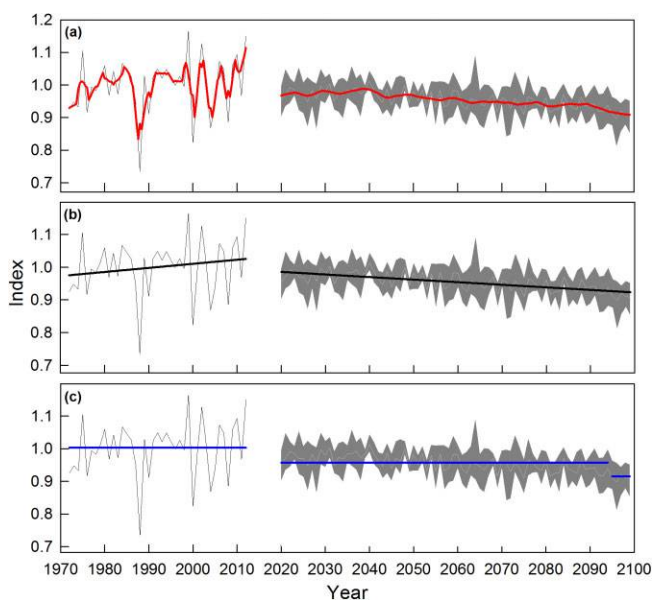


Figure 4. Time series of observed standardised *Vitis vinifera* radial growth (—) and projected growth (—) fitted with (a) a loess (local regression) smoothing spline (—); (b) trend lines (—); and (c) regime shift detections using the Rodionov (2004) method (—).

Future growth and yield

The projections of *V. vinifera* growth from HYDRUS have less variability than those observed due to the averaging of time series from each GCM. Each GCM simulates the physics of climate differently and will thus have different precipitation and temperature projections. Thus, we include both the minimum and maximum projection of yield for each year to show model uncertainties (Figure 4). By about 2070, however, even the maximum projection is consistently under the observed mean (Figure 4a), indicating that even with model uncertainties a decline in yield is projected. Further, the projections show a consistent and significant decrease in annual radial growth ($P < 0.001$), while the observed record shows no significant trend ($P = 0.591$) (Figure 4b) using the Mann-Kendall and Sen's slope analysis. The smoothed time series (Figure 4a), however, shows that from 2020 to 2040 the winegrape yield is fairly steady and does not show a continuous decrease until after 2040. The regime shift analysis (Rodionov 2004) indicates that the average annual grape yield for 2020/90 will be significantly ($P < 0.05$) lower than that for the observed period (Figure 4c). A second regime shift is projected to occur about 2095. These shifts will result in a total of a 12.4% decrease (4.3% for the first shift and an additional 8.5% decrease for the second shift) in projected average annual grape yield.

Interestingly, the observed winegrape yield record shows a non-significant but upward trend. These results follow findings from Jones et al. (2005) that reported many wine regions in the world (including California) are near their ideal climate for wine production and found a significant improvement in wine composition during the observed period. The inclusion of a quadric term, however, indicates that wine quality in these regions will plateau and eventually decline. Further, Webb et al. (2008) found a quadric relationship between wine price and climate (in their case summer temperature) for some winegrape cultivars in Australia, indicating that a small change in climate could lead to a large decrease in wine quality. While wine quality and winegrape yield are not directly comparable, we find similar results that indicate an initial increase (however, in our case not

significant) followed by a significant decline. Based on growth rings from *V. vinifera*, we find the beginning of the decline should start in the next 10 years and then decline gradually until 2040 and then decrease more rapidly (Figure 4a). Our results contrast with those from Santos et al. (2011), who found that winegrape yield would increase in the future in Portugal. The yield in the Santos et al. (2011) study, however, was estimated from the relationship between atmospheric variables and winegrape yield rather than the relationship between winegrape yield and vine growth rings, and they did not include soil moisture as a variable, while vine growth and yield in our study is strongly influenced by soil moisture.

Our findings suggest there is potential for using vine growth as a proxy of winegrape yield to represent vineyard specific data and provide a longer record of yield. More sites, however, need to be sampled at multiple locations for multiple winegrape types to determine how applicable our methods are in other regions. Climate change has and will continue to influence wine composition with high spatial variability (Nemani et al. 2001, Jones et al. 2005, Webb et al. 2007, 2008, Ramos et al. 2008), indicating that inter- and intra-regional environmental influences may mask the ability of the growth rings to work as a proxy to winegrape yield.

The vine stems used in this study come from a non-irrigated vineyard; thus, these findings have large implications for vineyard operators, indicating that irrigation may be needed in the future for continued success of the vineyard. In the projected future climate, vineyard operators would have to either start irrigating or increase current irrigation amounts to continue producing yields at the same level, creating higher infrastructure expenses and overall water costs for wine production. Further, grapevine cultivars have an ideal temperature range for the best quality of wine (Jones 2006), and the projected increases of temperature would not only have implications on soil moisture through evapotranspiration but could also lead to changes in microclimates requiring vineyards to potentially change the cultivar of grape produced. Because grape yield and composition, however, are not closely coupled (Jones and Davis 2000), drawing conclusions about the cost-effectiveness of the operation of a vineyard in a changing climate is complex. Wine quality will often increase with decreasing yield within a range, and thus increases in wine quality could continue as Jones (2006) also predicted. While lower yield can lead to higher wine quality, vineyard operators are still challenged financially, and determining the financial tipping point of where the cost of lower yields exceeds the price received for higher wine quality is difficult to determine. Regardless, our results indicate that the next ca. 80 years will possibly witness drastic changes to the climate of the NCAVA and have some significant management implications.

Conclusions

We found promising results using a new technique to examine how climate change will influence winegrape production. We found that grapevine radial growth and winegrape yield are significantly correlated, and both have a similar climate response to winegrape yield, indicating that growth rings of *V. vinifera* can be used as a proxy for winegrape yield. We used the HYDRUS model to project future vine growth based on projected future soil moisture and found that a gradual but consistent decrease in vine growth is projected, which can be used as a proxy for winegrape yield. Testing this method at multiple vineyards is needed, as well as examining potential differences between grapevine cultivars. To better assess how

this decline compares with the historical range in variability in vine growth and wine production, older vines need to be examined.

Vineyards in the NCVA have individual vines that are over 100 years old, indicating that a longer reconstruction of winegrape yield might be possible. Historical documentation, however, on how these long-lived vines have been managed through irrigation may confound their use. Regardless, efforts should be made to capture as much information as possible, for the reconstruction of agriculture yields using growth rings [a subfield in dendrochronology, called dendroagronomy; Maxwell and Knapp (2012), Maxwell et al. (2013)] could create data that would place the projected decline in a historical context. This information would be particularly relevant to vineyard operators faced with impending decisions of best management practices and adaptation to current and future climatic change.

The projected decrease in grapevine growth and winegrape yield would have large implications for the wine industry, especially to growers, requiring either the initiation or enhancement of irrigation, increasing the cost of growing grapes. In addition, increased demand on water resources for other societal needs may further limit irrigation potential within California. Therefore, if climate conditions continue to change to warmer and potentially drier conditions, the economic sustainability of some vineyards may be challenged, and producers may be forced to move their operations to areas with a more ideal climate for sustainable grapevine growth and/or greater access to water for irrigation needs.

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Supporting information

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Table S1. Values for raw yield and standardised yield.