Spatial Analysis of Climate in Winegrape Growing Regions in the Western United States

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Abstract: Knowledge of the spatial variation in temperature in wine regions provides the basis for evaluating the general suitability for viticulture, allows for comparisons between wine regions, and offers growers a measure of assessing appropriate cultivars and sites. However, while tremendous advances have occurred in spatial climate data products, these have not been used to examine climate and suitability for viticulture in the western United States. This research spatially maps the climate in American Viticultural Areas (AVAs) throughout California, Oregon, Washington, and Idaho using the 1971–2000 PRISM 400 m resolution climate grids, assessing the statistical properties of four climate indices used to characterize suitability for viticulture: growing degree-days (GDD, or Winkler index, WI), the Huglin index (HI), the biologically effective degree-day index (BEDD), and average growing season temperatures (GST). The results show that the spatial variability of climate within AVAs can be significant, with some regions representing as many as five climate classes suitable for viticulture. Compared to static climate station data, documenting the spatial distribution of climate provides a more holistic measure of understanding the range of cultivar suitability within AVAs. Furthermore, results reveal that GST and GDD are functionally identical but that GST is easier to calculate and overcomes many methodological issues that occur with GDD. The HI and BEDD indices capture the known AVA-wide suitability but need to be further validated in the western U.S. Additionally, the research underscores the necessity for researchers, software developers, and others to clearly communicate the data time period and method of calculating GDD so that results can be correctly interpreted and compared.

Key words: climate, viticulture, temperature, degree-days, American Viticultural Area

Climate is arguably the most important factor in virtually every agricultural enterprise. Overall, a region's baseline annual and seasonal climate and its variability largely determine crop suitability, productivity, and quality. For viticulture and wine production, the spatial distribution of mesoclimates in a region is important for understanding cultivar suitability and potential wine styles (Winkler et al. 1974, Carbonneau 2003). While many factors other than temperature drive viticultural suitability and wine production (Jackson and Lombard 1993, Jones and Davis 2000), simple to complex indices of temperature are the most commonly used measures by which regions are compared (Fregoni 2003, Tonietto and Carbonneau 2004, Blanco-Ward et al. 2007). The mostly frequently applied measure is the standard degree-day formulation first proposed by A.P. de Candolle in France during the mid-19th century (Seguin 1982) and further developed in California to include more objective fruit and wine composition and quality determinants (Amerine and Winkler 1944, Winkler et al. 1974). Other climate measures in viticulture suitability studies typically account for either simple temperature characteristics such as the mean temperature of the warmest month (Prescott 1965) or growing season (Jones 2006), heat accumulation or growing degree-day formulations that include moisture or solar radiation parameters (Branas 1974, Riou et al. 1994, Fregoni 2003), latitude-temperature indices (Kenny and Shao 1992), and multiparameter or multi-index methods that use combinations of temperature, relative humidity, sunshine hours, evapotranspiration, and continentality (Smart and Dry 1980, Tonietto and Carbonneau 2004). While the more complex measures show promise in certain specific areas of research (e.g., individual phenological events), they are limited by globally available data, do not have widespread use in general wine region climate comparisons, and entail more complicated calculations for the typical grower.

Historically, a given region's climate and suitability for viticulture were assessed via climate station analyses, which seldom depict the spatial variation of climate in actual or prospective vineyard sites within wine-producing regions. As a result, reference vineyard networks were developed within regions to better capture the spatial climate

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characteristics (Jones and Davis 2000, Battany 2009). However, low network density does not account for all mesoclimatic structure. To overcome these issues, climatologists developed spatial data products through interpolation of existing long-term, quality-controlled data sources. Numerous techniques such as kriging and smoothing splines (e.g. in ANUSPLIN, version 4.3; Australian National University) have been proposed to produce interpolated surfaces of valuable meteorological inputs at different spatial and temporal scales. The results are spatial climate products at daily or monthly time scales and at a range of spatial scales (Willmott and Robeson 1995) such as Daymet (Thornton et al. 1997), PRISM (parameter-elevation relationships on independent slopes model) (Daly et al. 2008), and WorldClim (Hijmans et al. 2005). However, even with these tremendous advances in spatial climate data products, to our knowledge there has been no large-scale update of climate suitability for viticulture in western U.S. wine regions over the last 30 years.

Therefore, the purpose of this research is to provide an updated analysis and overview of climate indices considered important for understanding viticultural suitability within the western U.S. wine regions. Our focus was to develop regional climate assessments for four commonly used indices: average growing season temperatures (GST) (Jones 2006); simple growing degree-days (GDDs) classified by the Winkler index (WI) (Amerine and Winkler 1944, Winkler et al. 1974); the Huglin index (HI) (Huglin 1978); and the biologically effective degree-day index (BEDD) (Gladstones 1992). Overall, the goal was to provide a method for more appropriate and accurate climate comparisons between wine-producing regions in the western U.S. and other regions worldwide than can be obtained through static climate station data.

Materials and Methods

This research used PRISM, the official spatial climate data set of the U.S. Department of Agriculture (Daly et al. 2008). PRISM creates 1971–2000 mean monthly minimum and maximum temperature data as 15 arc-second (~400 m) grids through a climate station interpolation method that reflects the current state of knowledge of U.S. spatial climate patterns. The PRISM model interpolates a comprehensive collection of stations from many networks, including the National Weather Service Cooperative Network, USDA Snow Telemetry, U.S. Forest Service Remote Automatic Weather Stations, local networks, and snow courses (16,615 precipitation sites and over 11,500 temperature sites were used in the U.S.) and then constructs a continuous grid data set for locations without stations. PRISM does this by calculating a climate-elevation regression for each digital elevation model (DEM) grid cell, and stations entering the regression are assigned weights based primarily on the physiographic similarity of the station to the grid cell (Daly et al. 2008). The model accounts for location, elevation, coastal proximity, aspect, vertical differences in atmospheric layers, and orographic effects. The PRISM data set also underwent comprehensive peer review to incorporate local knowledge and data into the development process (Daly et al. 2008). While there are other spatial climate data sets, such as Daymet (Thornton et al. 1997) and WorldClim (Hijmans et al. 2005), PRISM has been validated in the mountainous and coastal areas of the western U.S. (Daly et al. 2008), showing greater accuracy in regions characterized by sparse data coverage, large elevation gradients, rain shadows, inversions, cold air drainage, and coastal effects. Furthermore, PRISM has been validated to closely match values at remote vineyard locations (G. Jones, unpublished data, 2005), applied in viticulture zoning studies in the western U.S., and used in other applications such as regional snow assessment (Nolin and Daly 2006), river forecast and water balance assessments (National Oceanic and Atmospheric Administration; http://www.cnrfc.noaa.gov/), and pest and plant disease modeling (Integrated Plant Protection Center; http://ipmnet.org/).

The four climate measures used in this analysis were chosen based on their applicability in understanding general wine-region climate characteristics, ability to depict cultivar suitability or wine style potential, and widespread acceptance and use in different regions (e.g., WI in the U.S. and HI in Europe) (Table 1). Each measure described below was calculated from the PRISM grids for the 1971–2000 monthly climate normals for California, Oregon, Washington, and Idaho. The spatially explicit climate data allowed us to calculate the climate measures for every 400 x 400 m grid cell in the western U.S., allowing for the spatial mapping of climate over the entire domain instead of relying on station comparisons as has been done in the past. With a grid spacing of ~400 m, each climate grid cell represents ~16 hectares.

A growing season average temperature index (GST) was calculated by taking the average of the seven months of the growing season (Apr–Oct) and the result was classified into five groups according to cool, intermediate, warm, hot, and very hot climate-variety maturity types (Jones et al. 2005, Hall and Jones 2009). The simple GST index correlates broadly to the maturity potential for winegrape varieties grown across many wine regions (Jones 2006) and provides the basis for placing latitudinal boundaries on viticulture zones in both hemispheres (Gladstones 2004, Schultz and Jones 2008).

Growing degree-days (GDDs) were calculated from the climate grids based upon the standard simple degree-day formulation using average temperatures above a 10°C base for April through October (Table 1). While an upper temperature threshold to the standard degree concept is undoubtedly warranted (McIntyre et al. 1987, Snyder et al. 1999), the goal of this research was not to prove that one threshold or another is more applicable, but simply to update the values to the 1971–2000 climate normals and provide a measure comparable to the original GDD method (Amerine and Winkler 1944, Winkler et al. 1974). Furthermore, the standard Winkler index (classed GDD) was developed using five broad classes (regions) for general wine styles, which did not provide an upper or lower class limit (Winkler et al. 1974). Therefore, this research examined the data over the western U.S. to help establish a lower Winkler Region I limit and an upper Winkler Region V limit (Table 1).

The Huglin index (HI) represents a similar heat summation formulation to the GDD with an adjustment that gives more weight to maximum temperatures and is multiplied by a coefficient of correction (*K*) which takes into account the average daylight period for the latitude studied (Huglin 1978) (Table 1). When used in Europe and elsewhere, the HI is a six-month index summed over the Apr–Sept growth period, as Huglin surmised that heat accumulation in October was less important, even though many regions in Europe harvest in October. Comparisons between the HI calculated for Apr–Oct and Apr–Sept are highly correlated ($r > 0.95$) for many regions (authors' own calculations), and while Apr–Sept represents one less month than standard GDD formulation, it was adhered to for ease of comparison with published data. In addition, the HI latitudinal correction was developed for the latitudes of European viticulture as a linear response to increasing day lengths (K = 1.02 at 40°N to K = 1.06 at 50°N). The correction as originally applied was by the latitude of each weather station in each region (Huglin 1978). However, with the advent of spatial data processing, this research was able to enhance the original HI latitudinal adjustment by applying a grid cell correction to all latitudes over the western U.S. (with the day length effect starting at 33.3°N). This effectively adjusts all 400 m grids over California, Oregon, Washington, and Idaho for the latitude-day length effect. The original class structure of the HI (Huglin 1978) was preserved in the mapping by using six classes based upon cultivar suitability with lower (1200 C° units) and upper bounds (3000 C° units) (Table 1).

The BEDD index was developed by Gladstones (1992) after observing that plant growth and phenological development respond to temperature in a nonlinear fashion and finding potential limitations to the standard WI and HI approaches. As such, the BEDD has three adjustments: (1) the interval of effective heat summation is considered between

Table 1 Climate variables derived for the western U.S. using the PRISM 1971–2000 climate normals along with the number and percent of total AVAs (n = 135) with median climate index values in each class (Table 3). Note that the GDD classes are based upon limits originally given by Amerine and Winkler (1944) along with lower and upper bounds for Region I and Region V as detailed in the text. Also note that the class names given below are not directly comparable (e.g., GST cool does not necessarily compare to HI cool).

Variable	Equation	Months	Class limits		AVAs (n)	AVAs (%)
Average growing season temperature (GST, °C)	$\dfrac{\sum_{Apr1}^{Oct31}(T_{max}+T_{min})/2}{n}$	Apr–Oct	Too cool	<13°C	0	0.0
			Cool	13–15°C	9	6.7
			Intermediate	15–17°C	28	20.7
			Warm	17–19°C	61	45.2
			Hot	19–21°C	34	25.2
			Very hot	21–24°C	3	2.2
			Too hot	>24°C	0	0.0
Growing degree-days (GDD, C° units)[a]	$\sum_{Apr1}^{Oct31}\max[([T_{max}+T_{min}]/2)-10,0]$	Apr–Oct	Too cool	<850	0	0.0
			(Region I)	850–1389	23	17.0
			(Region II)	1389–1667	34	25.2
			(Region III)	1667–1944	44	32.6
			(Region IV)	1944–2222	25	18.5
			(Region V)	2222–2700	9	6.7
			Too hot	>2700	0	0.0
Huglin index (HI, C° units)	$\sum_{Apr1}^{Sep30}\max([([T_{mean}-10]+[T_{max}-10])/2],0)\cdot K$	Apr–Sept	Too cool	<1200	0	0.0
			Very cool	1200–1500	1	0.7
			Cool	1500–1800	11	8.1
			Temperate	1800–2100	20	14.8
	where *K* is an adjustment for latitude/day length[b]		Warm temperate	2100–2400	38	28.1
			Warm	2400–2700	44	32.6
			Very warm	2700–3000	19	14.1
			Too hot	>3000	2	1.5
Biologically effective degree-days (BEDD, C° units)	$\sum_{Apr1}^{Oct31}\min[(\max[([T_{max}+T_{min}]/2)-10,0]),9]\cdot DTR_{adj}\cdot K$	Apr–Oct	Too cool	<1000	2	1.5
				1000–1200	9	6.7
				1200–1400	8	5.9
				1400–1600	21	15.6
	where $DTR_{adj}=\begin{cases}0.25[DTR-13], & [DTR]>13\\ 0, & 10<[DTR]<13\\ 0.25[DTR-10], & [DTR]<10\end{cases}$			1600–1800	31	23.0
				1800–2000	51	37.8
				2000–2200	13	9.6
	where *K* is an adjustment for latitude/day length[b]		Too hot	>2200	0	0.0

[a] GDD classes (regions) are based on rounded °F limits as defined by Winkler et al. (1974) (in parentheses), which produce nonrounded classes in °C units.

[b] *K* is a latitude coefficient that takes into account increasing day lengths starting from 1.0 at 33.3° increasing incrementally poleward and is based on day lengths using Julian day and latitude. See Hall and Jones (2010) for calculation details.

10°C (base temperature) and 19°C (upper threshold); (2) a latitude adjustment to account for an increasing day length effect (the same as HI); and (3) a diurnal temperature range adjustment (DTR_{adj}, upward if the DTR is >13°C and downward if <10°C) (Gladstones 1992). Once the corrections for latitude and diurnal temperature range were applied to the monthly BEDD indices, a seasonal total was calculated by summing the months from April to October. The 10 and 19°C thresholds limit any given day to 9 C° units, individual months to 270 or 279 C° units, or the season to 1926 C° units, although the diurnal temperature range adjustment can either add or subtract values from the theoretical maximum. BEDD was then classed into six groups for this analysis representing cool regions with low/late maturity potential to hot regions with high/earlier maturity potential (Table 1).

To assess the spatial climate characteristics of these four climate indices in the western U.S. wine regions, this research used American Viticultural Area (AVA) boundaries created from federally approved descriptions (Code of Federal Regulations 2008). The first U.S. region approved was the Augusta AVA in Missouri in 1980, and today there are nearly 200 AVAs in 31 states. For this research the AVA boundaries were digitized from the approved boundary descriptions, resulting in a total of 131 individual AVAs in California (109), Oregon (16, three shared with Washington and one with Idaho), Washington (9, three shared with Oregon), and Idaho (1, shared with Oregon) (Figure 1). Of the 131 AVAs, 129 were approved as of the beginning of 2008 and two were under review (Calistoga and Tulocay) but were included in the analysis.

Using a geographic information system (ArcGIS version 9.3; ESRI, Redlands, CA), the area and elevation of the digitized AVAs were determined (Table 2) using a 30 m digital elevation data set (USGS 1993) for the western U.S. (Figure 1). The AVA boundaries were then used with the spatial climate grids for GST, GDD, HI, and BEDD to assess the spatial characteristics of each AVA climate (Table 3). The process analyzed all 400 m grids that fell within each AVA, producing quantile statistics for each AVA (minimum, 25%, median, 75%, and maximum values), which was the most practical measure of characterizing the entire within-AVA climate, addressing the problem that many of the subjectively constructed AVA boundaries include areas that are not planted (and likely never will be). While low-relief AVAs are best represented by the median or the interquartile range statistics, the outlier zones in many regions (i.e., too high of elevation and/or too cold as in the Columbia Valley AVA) render them less than ideal statistical measures for all AVAs, where the median to the maximum or 75% to the maximum may well be more indicative of the actual suitable areas. Therefore, we present the entire quantile statistics allowing for an AVA-by-AVA assessment of the best statistical parameters that define those areas.

Results

AVAs across the western U.S. range from very large (over 750,000 ha, or 7500 km^2) to small (less than 1,000 ha, or 10 km^2) (Table 2, Supplemental Table 1). Columbia Valley AVA is the largest, spanning over 4.6 million ha (46000 km^2) in both Washington and Oregon (Figure 1). Cole Ranch AVA in Northern California is the smallest at ~80 ha (0.8 km^2). The median AVA in the western U.S. is 15,110 ha (151.1 km^2), roughly the size of the Knights Valley AVA (Table 2).

Elevations for western U.S. AVAs range from a minimum at sea level (e.g., Puget Sound, Los Carneros) to over 1500 m (e.g., Sierra Foothills, Central Coast). The lowest median elevations of ~1 m are in the Delta region of the California Central Valley (e.g., Clarksburg). The highest median elevation of 880 m is in the Snake River Valley of Idaho and Oregon (Table 2). The smallest range in elevation (<2–3 m) is throughout the AVAs in the Delta region. At 1,953 m, Southern Oregon and its sub-AVA the Rogue Valley have the greatest elevation range.

In general the median AVA values for the four climate indices are highly correlated (0.89 < r < 0.99) over the entire western U.S. AVAs, indicating that each index depicts similar spatial climate characteristics (Figure 2). The highest correlation is between GST and GDD (r = 0.99), indicating that these two indices fundamentally capture the

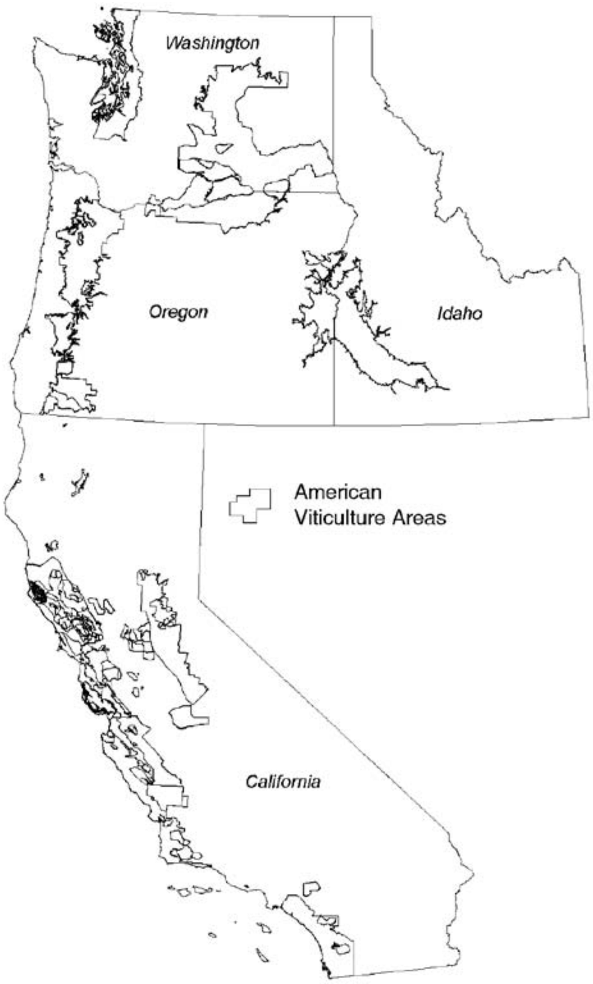

Figure 1 American Viticultural Areas (AVAs) over the western United States (California, Oregon, Washington, and Idaho), as of 1 Jan 2008.

same climate information. The lowest correlations (0.89 < *r* < 0.91), with more curvilinear relationships, are between the BEDD and the other three indices and are due to the additional DTR adjustment used in the BEDD (Gladstones 1992). Similar correlations and functional relationships between the climate indices have been documented for Australia (Hall and Jones 2010). However, while the median AVA values are highly correlated, the class names and limits as originally applied to each index (Table 1) are not directly comparable (e.g., the cool GST class limits do not necessarily equate to the cool HI class limits).

Each index depicts a generally intuitive spatial framework with warm to hot conditions for viticulture in south-central and southeastern California, to cool and cold conditions north into Washington, and cooler conditions with increasing elevation throughout the western U.S. The spatial structure of GST (Figure 3) reveals predominately cool to intermediate climate types throughout much of the intermountain valleys from the Puget Sound south through Oregon, in the Snake River Valley of Idaho and Oregon, and along the narrow California coastal zones. Warmer climate types occur throughout a broad area of the Columbia Valley of Washington and Oregon, throughout the intercoastal valleys and Sierra Nevada foothills of California, and into the middle portion of the Central Valley. The hottest climate types suitable for viticulture are in the northern and southern portions of the Central Valley. Overall, the median AVA GST averages 18.0°C and ranges from a low of 13.9 and 14.0°C in the Puget Sound and Columbia River Gorge AVAs, respectively, to 21.7°C in the Madera AVA of California (Table 3, Supplemental Table 2). The range in median AVA GST values is approximately normally distributed with wine regions spread from cool to very hot climate maturity groupings (Jones 2006, Hall and Jones 2009), with over 45% of all AVAs categorized in the warm climate type between 17°C and 19°C (Table 1).

Table 2 Examples of western U.S. American Viticultural Area (AVA) elevation and area characteristics. (See Supplementary Table 1 for complete list of all 135 western U.S. AVAs.)

			Elevation (m)			
AVA	**State**	**Area[a] (km^2)**	**Median**	**Max**	**Min**	**Range**
Columbia Valley	OR/WA	46106.1	402	1559	22	1537
Central Coast	CA	22159.4	325	1670	0	1670
Snake River Valley	ID/OR	21651.9	880	1471	549	922
Willamette Valley	OR	13875.9	122	797	6	791
Puget Sound	WA	11654.0	78	963	0	963
Sierra Foothills	CA	10806.8	470	1701	54	1647
Southern Oregon	OR	9245.3	406	1987	34	1953
Rogue Valley	OR	4638.4	576	1987	244	1743
Umpqua Valley	OR	2805.8	236	718	34	684
Paso Robles	CA	2464.2	398	745	176	569
Lodi	CA	2195.2	24	151	0	152
Madera	CA	1851.1	65	148	38	110
Santa Cruz Mountains	CA	1661.0	337	1069	5	1064
Napa Valley	CA	1623.9	248	1175	0	1175
Walla Walla Valley	OR/WA	1306.3	317	784	122	662
Columbia River Gorge	OR/WA	756.3	375	849	43	806
Mendocino	CA	715.4	375	1139	124	1015
Russian River Valley	CA	631.7	62	438	15	423
Temecula Valley	CA	373.9	426	845	191	654
Wahluke Slope	WA	334.4	240	475	122	353
Alexander Valley	CA	316.9	148	746	48	698
Rattlesnake Hills	WA	301.2	547	850	365	485
Clarksburg	CA	275.4	1	3	0	3
Anderson Valley	CA	236.2	217	536	60	476
Yamhill-Carlton District	OR	235.3	122	365	51	314
Eola-Amity Hills	OR	158.8	127	314	57	257
Los Carneros	CA	151.3	29	380	0	380
Knights Valley	CA	151.1	257	1186	65	1121
Santa Rita Hills	CA	135.2	166	461	59	402
Carmel Valley	CA	73.9	405	778	161	617
Dundee Hills	OR	50.8	122	301	54	247
Hames Valley	CA	49.9	234	374	171	203
St. Helena	CA	37.3	89	197	59	138
Yountville	CA	33.7	81	358	18	340
Red Mountain	WA	18.4	208	311	152	159
Cole Ranch	CA	0.8	474	524	456	68

[a] Area rounded to the nearest 0.1 km^2 (10 ha); approximate due to the grid-based estimation procedure.

There are similar patterns for GDD (WI) regions (Figure 3), where Region I is mostly confined to western Oregon and Washington, the coastal zone of California, higher up in the Sierra Nevada foothills, and along valley extensions in parts of Washington, Oregon, and Idaho. Region II is found broadly throughout the Columbia Valley, the Rogue Valley, in the Snake River Valley, and along an elevation band of the California intercoastal valleys and foothills. In California, Region III locations are found slightly more inland than those of Region II and in areas of lower elevation along the Sierra Nevada foothills. Outside California, Region III is limited to only a few areas of the Columbia Valley (Figure 3). Region IV is limited to California only, with prominent areas on the eastern fringes of the coastal mountains, the western periphery of the Central Valley, and through the Central Valley east of San Francisco into the Sierra Nevada foothills. Region V encompasses broad areas throughout the Central Valley.

However, the original Winker region formulation did not provide both the lower and upper classes limits, which would lead to all areas below 1389 GDD belonging to Region I and all areas above 2222 GDD belonging to Region V. The results here suggest that the upper limit of Region V is near 2700, as this encompasses the median values of the warmest region, the Madera AVA (Table 3). Similarly, to encompass the median values of the coolest regions, the lower limit of Region I would need to be set to 850 GDD. Using these criteria, GDDs average 1,711 units over all AVAs ranging from a median low of 851 and 903 in the Puget Sound and Columbia River Gorge AVAs, respectively, to a median

Table 3 Examples of western U.S. American Viticultural Area (AVA) 1971–2000 PRISM-calculated quantile statistics for growing season average temperature (GST, °C), growing degree-days (GDD, C° units), Huglin index (HI, C° units), and biologically effective degree-days (BEDD, C° units). (See Supplementary Table 2 for complete list of all 135 western U.S. AVAs.)

	GST avg (°C)					GDD					HI					BEDD				
AVA Name	**Min**	**25%**	**Median**	**75%**	**Max**	**Min**	**25%**	**Median**	**75%**	**Max**	**Min**	**25%**	**Median**	**75%**	**Max**	**Min**	**25%**	**Median**	**75%**	**Max**
Alexander Valley	17.1	18.0	18.1	18.3	19.1	1521	1705	1741	1785	1957	1844	2297	2375	2455	2651	1381	1774	1874	1914	2003
Anderson Valley	15.9	16.5	17.2	17.6	18.3	1254	1400	1533	1630	1773	1784	2008	2187	2313	2474	1374	1554	1694	1803	1914
Carmel Valley	15.8	16.2	16.5	16.8	17.2	1236	1325	1392	1459	1540	1790	1906	1946	1978	2068	1418	1471	1502	1532	1585
Central Coast	13.1	16.5	17.8	18.8	21.5	674	1398	1677	1877	2469	979	1832	2278	2626	2955	639	1425	1737	1988	2166
Clarksburg	20.0	20.1	20.2	20.3	20.4	2135	2154	2176	2198	2230	2746	2764	2788	2813	2834	1994	2002	2005	2009	2021
Cole Ranch	17.9	17.9	18.0	18.0	18.0	1701	1703	1714	1724	1724	2372	2396	2412	2420	2420	1774	1778	1781	1785	1795
Columbia River Gorge	12.6	13.5	14.0	14.7	16.9	686	830	903	1028	1490	1264	1515	1599	1742	2215	761	959	1031	1136	1486
Columbia Valley	9.8	15.2	16.2	16.9	18.3	382	1167	1329	1483	1779	823	1938	2141	2290	2590	416	1244	1373	1486	1655
Dundee Hills	14.3	14.7	15.0	15.2	15.4	940	1022	1081	1115	1154	1532	1640	1725	1764	1822	1009	1115	1176	1213	1255
Eola-Amity Hills	14.2	14.6	14.9	15.1	15.3	935	1010	1059	1093	1138	1502	1660	1739	1794	1850	1003	1120	1186	1230	1282
Hames Valley	18.8	19.2	19.4	19.6	19.8	1880	1969	2018	2047	2099	2726	2798	2831	2847	2868	2074	2131	2143	2150	2159
Knights Valley	14.7	17.7	18.3	18.5	19.2	1057	1644	1788	1826	1967	1598	2090	2416	2503	2641	1159	1544	1852	1931	2009
Lodi	20.0	20.2	20.3	20.4	20.7	2133	2175	2211	2225	2290	2743	2781	2797	2828	2906	1904	1958	1980	2001	2022
Los Carneros	17.0	17.4	17.6	18.0	19.5	1497	1593	1637	1705	2027	2007	2126	2191	2270	2579	1581	1693	1749	1813	1932
Madera	21.2	21.4	21.7	21.8	22.5	2409	2450	2511	2537	2686	3009	3055	3131	3175	3325	2044	2069	2099	2119	2175
Mendocino	16.9	18.0	18.3	18.5	19.5	1489	1713	1774	1824	2046	1899	2330	2461	2562	2644	1345	1681	1838	1927	1978
Napa Valley	15.1	18.2	18.8	19.2	20.4	1131	1753	1883	1970	2235	1668	2317	2504	2601	2884	1210	1743	1850	1923	2060
Paso Robles	16.4	18.3	18.9	19.2	20.2	1361	1779	1903	1978	2177	2048	2585	2681	2736	2900	1619	1982	2032	2059	2158
Puget Sound	10.4	13.6	13.9	14.3	15.2	336	785	851	923	1112	697	1319	1414	1497	1725	324	816	890	967	1167
Rattlesnake Hills	13.8	15.0	15.6	16.2	16.8	921	1125	1205	1340	1452	1589	1913	2061	2191	2305	1029	1232	1340	1441	1541
Red Mountain	16.8	17.0	17.0	17.1	17.3	1466	1493	1505	1520	1557	2271	2302	2330	2337	2378	1458	1509	1526	1533	1562
Rogue Valley	10.5	14.9	15.7	16.2	17.0	486	1101	1225	1326	1509	853	1794	2011	2168	2391	440	1231	1386	1522	1715
Russian River Valley	16.3	17.0	17.1	17.2	18.4	1347	1492	1520	1539	1796	1901	2107	2152	2167	2473	1505	1703	1747	1756	1951
Santa Cruz Mountains	14.3	16.8	17.2	17.6	18.5	913	1450	1553	1628	1823	1262	1844	2005	2118	2358	934	1442	1554	1666	1882
Santa Rita Hills	16.1	16.8	17.0	17.2	19.0	1314	1455	1496	1532	1938	1654	1885	1956	1997	2177	1335	1525	1586	1629	1710
Sierra Foothills	14.2	19.0	19.8	20.4	22.7	1008	1926	2098	2218	2718	1472	2556	2715	2839	3343	1023	1749	1852	1943	2205
Snake River Valley	13.0	15.6	16.1	16.5	18.6	811	1241	1329	1402	1836	1406	2095	2207	2301	2645	898	1365	1436	1499	1702
Southern Oregon	10.8	14.9	15.4	15.9	17.1	469	1067	1165	1266	1509	848	1739	1900	2069	2391	493	1197	1314	1436	1715
St. Helena	18.7	18.8	18.9	19.0	19.3	1870	1876	1896	1922	1997	2552	2566	2571	2592	2629	1905	1942	1954	1959	1987
Temecula Valley	19.1	20.3	20.6	20.9	21.6	1957	2198	2264	2342	2478	2222	2602	2755	2907	3090	1642	1846	1975	2082	2190
Umpqua Valley	13.3	14.9	15.2	15.5	16.4	786	1053	1115	1184	1371	1296	1719	1827	1915	2198	823	1177	1266	1332	1564
Wahluke Slope	15.1	16.9	17.2	17.5	18.2	1144	1484	1545	1602	1758	1947	2311	2371	2422	2539	1252	1495	1531	1561	1622
Walla Walla Valley	13.4	16.7	17.1	17.3	17.5	849	1444	1528	1564	1617	1582	2202	2296	2331	2405	1044	1408	1480	1510	1565
Willamette Valley	12.3	14.7	15.0	15.2	16.3	596	1014	1081	1119	1354	1087	1658	1748	1784	1969	621	1116	1195	1224	1370
Yamhill-Carlton District	13.8	14.7	15.0	15.2	15.5	858	1029	1072	1109	1180	1444	1660	1723	1775	1863	934	1119	1173	1216	1289
Yountville	18.3	18.7	18.9	19.0	19.3	1788	1864	1898	1927	1993	2393	2499	2521	2545	2663	1814	1916	1924	1934	1959

high of 2511 in the Madera AVA. In terms of median values the AVAs predominately fall into Region III (33%) followed by Region II (25%) and Region IV (19%) (Table 1).

The other two indices (HI and BEDD) produce broadly similar patterns of climates across the western U.S. (Figure 4). However, because of a latitude adjustment for day length influences, both the HI and BEDD suggest greater viticultural suitability over much of Oregon, Washington, and Idaho than either GST or GDD. For the HI, much of the Pacific Northwest falls into very cool and cool classes while broad areas of eastern Washington and Oregon are classified as temperate, warm temperate, and warm. In California the HI depicts much of the Central Valley as very warm or too hot, while the intercoastal valley AVAs span cool to warm. The median HI averages 2347 units (warm temperate) over all AVAs in the western U.S., with a low of 1414 in the Puget Sound AVA and a high of 3131 in the Madera AVA. These values place the Puget Sound AVA into the very cool to cool class, but still suitable as compared to marginally suitable on the GDD, while the Madera AVA is considered too hot on the HI. The highest frequency HI classes over the western U.S. are warm temperate (28%) and warm (33%). The BEDD depicts a spatial pattern intermediate to GDD and HI, with cool to intermediate maturity classes dominating the Willamette and Umpqua Valley AVAs of Oregon, the California coastal zones and intermediate elevations in the Sierra Foothills AVA, and surrounding areas of the Columbia River Valley AVA (Figure 4). The California intercoastal valley AVAs fall more into the intermediate to warm maturity classes on the BEDD. Over all of the AVAs, the median BEDD averages 1717 with a range from 890 in the Puget Sound AVA to a maximum of 2143 in the Hames Valley AVA, located at the southern end of the Monterey Valley AVA in California. The distribution of the median AVA BEDD values is slightly skewed to the higher maturity classes, with over 60% of the AVAs in the fourth and fifth maturity classes (Table 1).

Examining the within-AVA spatial characteristics of the climate indices enhances the broad regional applicability of the results discussed above (Figure 5). For example, the Napa Valley AVA, which encompasses many smaller sub-AVAs, ranges from cool to hot climate types for GST, Region I to a lower Region V for GDD, cool to very warm climate types for HI, and the lowest to the highest maturity classes for BEDD (Table 3). While the Napa Valley AVA has Region I through V zones, the distribution of climate types within the AVA reveals that it is predominantly a Region III (56%) and Region IV (30%) (Figure 5). A more inland region, the Walla Walla Valley AVA, ranges from cool to warm climate types using the GST index, with areas considered too cool in GDD (<Region I) to Region III, cool to warm on the HI, and range across the first three maturity classes on the BEDD. The spatial distribution of GDD in the Walla Walla Valley AVA reveals mainly Region II (82%) zones with some Region I (18%) areas (Figure 5). For warm regions with low topographical relief, the Lodi AVA and the Madera AVA both exhibit less spatial variability over each of the climate indices (Table 3). Lodi is mainly a hot climate type on the GST index, a Region IV and V in GDD (78% and 22%, respectively; Figure 5), very warm on

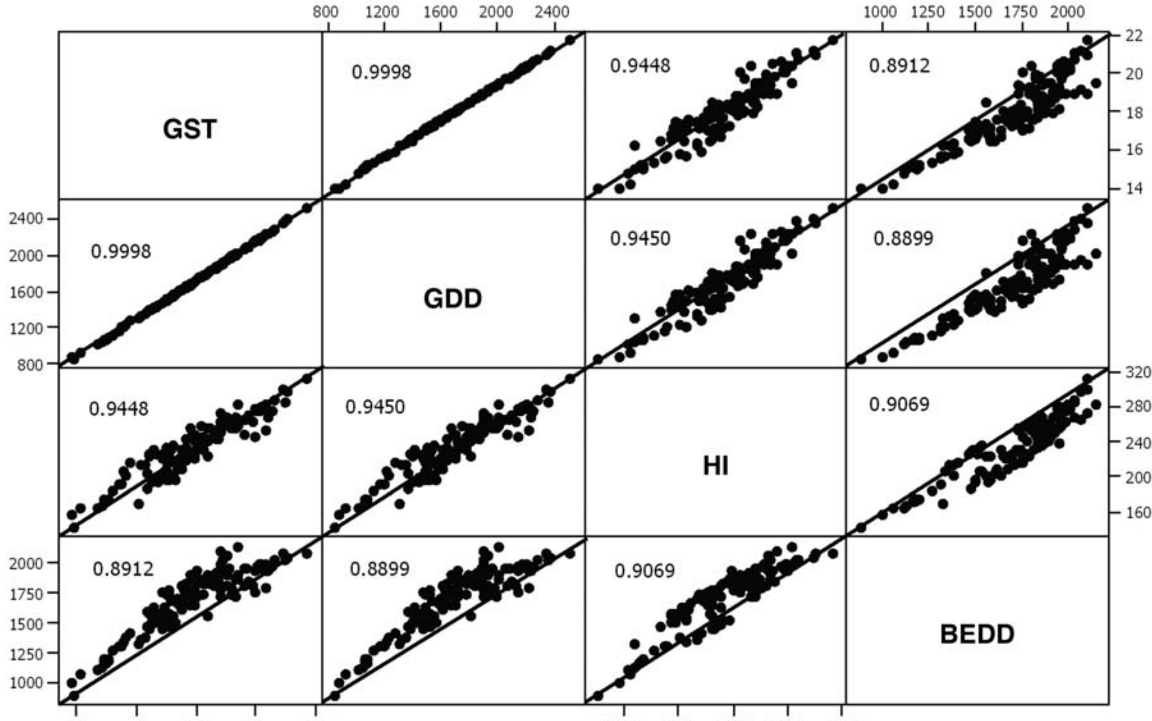

Figure 2 Matrix scatterplot and Pearson correlation coefficients illustrating the relationships of each of the median AVA values for the four climate indices. Each plotted point represents one AVA's median value for that index.

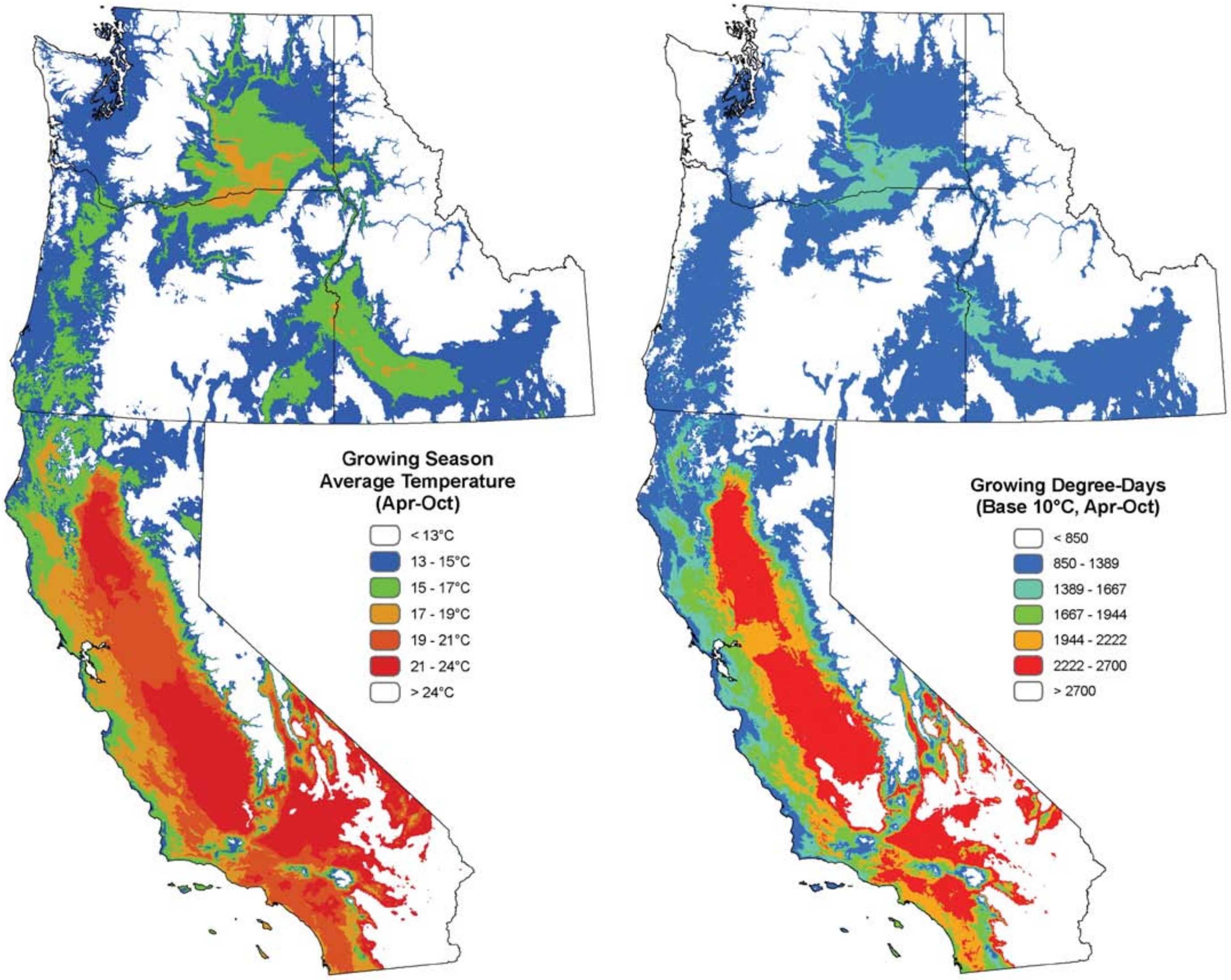

Figure 3 Average growing season temperatures (GST, left) and growing degree-days (GDD, right), over the western U.S. derived from PRISM 1971–2000 climate normals. GDD class limits originally given by Amerine and Winkler (1944) along with lower and upper bounds for Region I and Region V (see text). Class limits in legends are not directly comparable (e.g., the coolest GST class limits do not necessarily equate to the Region I class limits).

the HI, and in the upper two maturity classes on the BEDD. The warmer Madera is largely a very hot climate type on the GST index, a Region V in GDD (100%, Figure 5), considered too hot on the HI, and in the highest maturity class on BEDD. For a cooler region with moderate topographical relief, the Eola-Amity Hills AVA, a sub-AVA of the Willamette Valley, is cool to intermediate climate types for GST, an intermediate Region I (100%, Figure 5), cool to temperate for HI, and in the first and second maturity class for BEDD (Table 3). The level of spatial variability in climate within different AVAs can be significant (Figure 5), indicating that single climate stations cannot fully represent the climate within most AVAs. For example, this issue is clearly depicted for two AVAs with substantial differences in coastal versus inland influences: Anderson Valley and Paso Robles. Each one spatially spans three Winkler regions, with the Anderson Valley Region I–III (26%, 58%, and 16%, respectively) and the Paso Robles Region II–IV (14%, 49%, and 37%, respectively) (Figure 5).

Discussion

While the median AVA summary described above captures the overall framework of the climate indices over the western U.S. AVAs, elevation issues (Table 2) must be considered when assessing the quantile statistics within each AVA (Table 3). Note that the range between the minimum and maximum values represents the entire climatic range for each index within each AVA, not necessarily those areas that are or could be planted. For AVAs with low elevation ranges (~<200 m; Table 2), the entire quantile range from the minimum to the maximum values well represent the suitable climate characteristics of a given region (Table 3). For example, the Lodi AVA has a 152 m elevation range, reflected in its fairly narrow quantile distribution for all four climate indices. For AVAs with very high elevation ranges (~>1000 m; Table 2) the minimum to 25% to median quantile statistics represent higher elevation zones considered not suitable to viticulture. For example, the Rogue Valley AVA has an elevation range of 1743 m, which results in very low

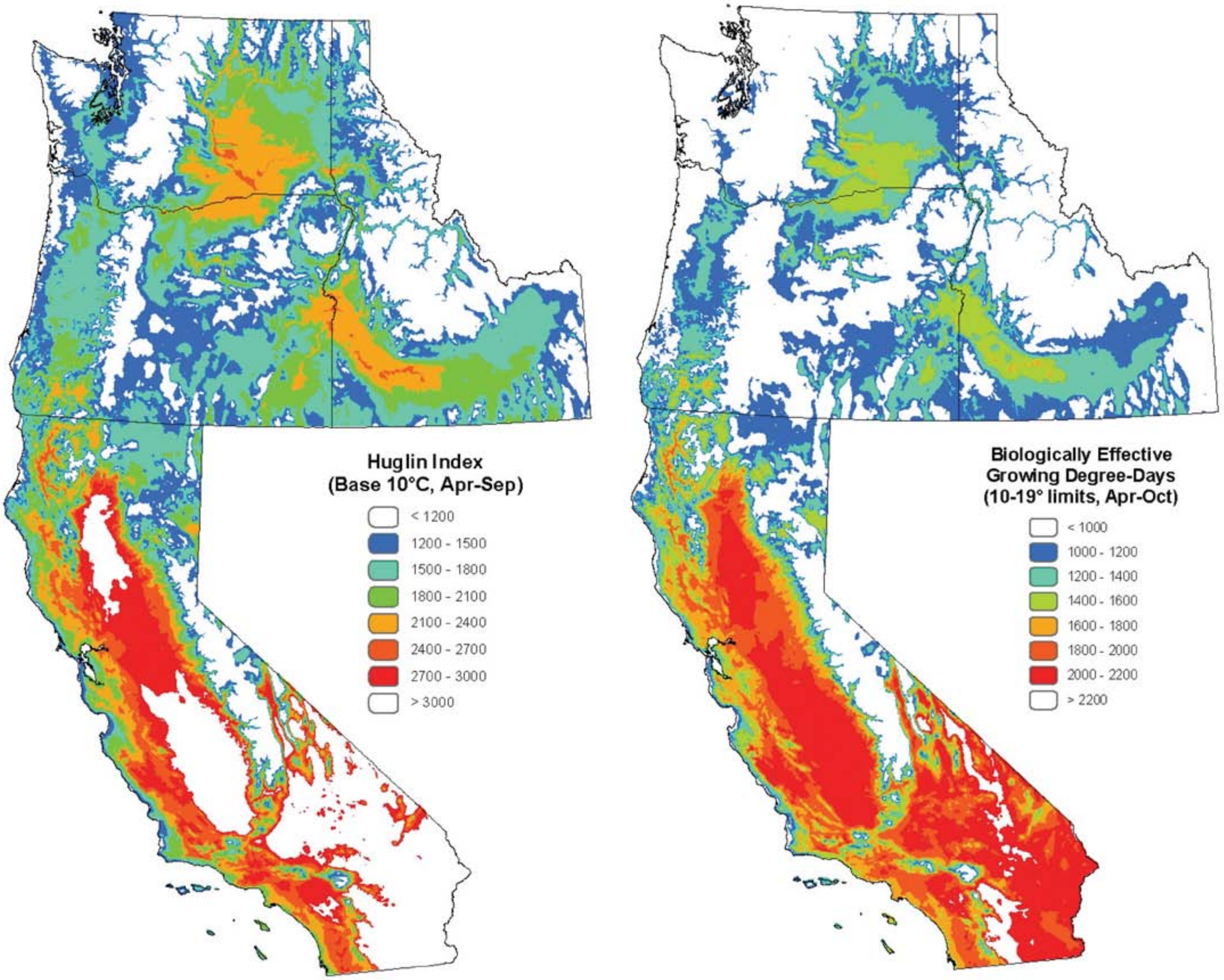

Figure 4 Huglin Index (HI) (left) and biologically effective growing degree-days (BEDD) (right), over the western U.S. derived from PRISM 1971–2000 climate normals. Class limits in legends are not directly comparable (e.g., the coolest HI class limits do not necessarily equate to the coolest BEDD class limits).

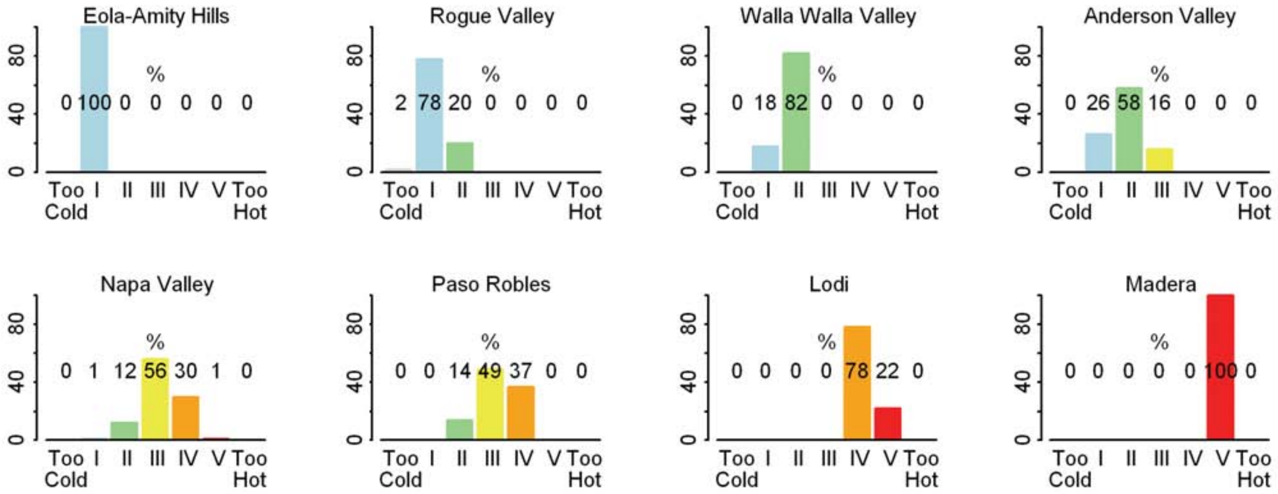

Figure 5 Distribution of Winkler region climate types (growing degree-days; GDD) within eight AVAs ranging from cool to hot growing conditions as given in Table 1. GDD classes are based upon limits originally given by Amerine and Winkler (1944) along with lower and upper bounds for Region I and Region V as detailed in the text.

index values at high elevations that would be considered climatically unsuitable to some zones with a mid-Region I using the minimum to 25% statistics (e.g., 486–1101 for GDD). The median to 75% to maximum statistics identifies the Rogue Valley AVA as an intermediate to warm climate type on the GST, a Region I to Region II in GDD (78% and 20%, respectively; Figure 5), temperate to warm-temperate on the HI, and in the second to fourth maturity classes on the BEDD (Table 3). The values match the reality in the Rogue Valley AVA, where a wide range of varieties can be successfully grown. For AVAs with elevation ranges between 200 and 1000 m, variations in the quantile statistics used to characterize those regions need to be assessed on an AVA by AVA basis. For example, with an elevation range of 567 m, the Paso Robles AVA has some higher elevations that are not likely to be planted, best represented by the minimum to 25% quantile statistics (Table 3, Figure 5), and leaving the suitable planting areas covering the climate range from the cooler sites (25% statistic) to the warmest sites (maximum statistic). Another determining issue is the orientation of the landscape to the coast or the valley. A given AVA might have a wide range of suitability whereby the range of quantile statistics would depend on the location and variety intended. For example, the Anderson Valley AVA with an elevation range of 476 m is oriented from the southeast to the northwest toward the coast. The southeasterly portion of the valley is warmer (better represented by the 16% of the AVA in Region III; Figure 5) and more appropriately represented by the 75% to maximum quantile statistics for each climate index (Table 3). However, the cooler climate of the northwestern portion of the valley is better captured in the minimum to 25% quantile statistics (represented by the 26% of the AVA in Region I; Figure 5), while intermediate locations fall in the 25% to 75% range (represented by the 58% of the AVA in Region II).

The value of knowing the full spatial range of climate indices within an AVA versus using single climate station values is further illustrated with examples from the 1971–2000 climate normals for stations across each of the five Winkler regions (Western Regional Climate Center; www.wrcc.dri.edu). For Region I, the Salem, Oregon climate station is 1278 GDD for the 1971–2000 climate normals, while the median Willamette Valley AVA GDD is 1081. In this case, Salem is clearly an urban station representing one of the warmest locations in the valley. The Sunnyside, Washington climate station, which is commonly used to characterize the Yakima Valley AVA, is 1561 GDD or a Region II. However, the Yakima Valley AVA is shown to contain zones with GDD from a high Region I to a high Region II (Table 3). For a Region III, the Paso Robles climate station has a 1971–2000 climate normal 2145 GDD. But this station is lower than the Paso Robles AVA median GDD and does not represent the 14% and 37% of the AVA, which are Region II and Region IV, respectively (Table 3, Figure 5). Examples of the warmer Region IV and V tend to show locations with low topographic and therefore low climate index variation that are somewhat better represented by stations. The Lodi, California climate station has a 1971–2000 climate normal 2145 GDD, which is in the lower quantile of the AVA statistics but in the same Region IV as 78% of the AVA (Figure 5). The Madera, California climate station 1971–2000 climate normal 2532 GDD is close to the Madera AVA median. However, both the Lodi and Madera climate station values still do not represent the range of ±100 GDD experienced across the AVAs.

Comparing the complete spatial depiction of the four climate indices across the western U.S. reveals significant broad (western U.S.) and within-AVA differences (Figure 2, Figure 3). For example, GST and GDD both produce the known pattern of general wine region suitability, yet these indices do not provide for much within-AVA differentiation (Figure 3). Even though the HI is summed over Apr–Sept instead of Apr–Oct as with the other indices, it correlates strongly with GST, GDD, and BEDD and depicts similar regional climate characteristics. However, the HI and BEDD tend to depict within-AVA spatial variations more strongly, but also include mostly untested land outside the generally recognized wine regions (Figure 4). Because of the addition of a day length adjustment, the HI also classes much of the Pacific Northwest as very cool and cool, closely matching the northern areas of Europe where the index was first applied (e.g., parts of Germany, Champagne, Chablis, Burgundy). This designation matches observations in the Puget Sound AVA where cool-climate varieties have been successfully grown in both trial and commercial vineyards (Moulton and King 2006). Furthermore, much of the Central Valley is depicted by the HI as too hot, whereas GDD shows it within the upper limit of suitability. The BEDD depicts a spatial pattern intermediate to GDD and HI, identifying the known cool to warm climate AVAs in the Pacific Northwest, but maintaining suitable zones at the warmer limits in California.

Similar research for Australia (Hall and Jones 2010) and Europe (Jones et al. 2009) has enabled an examination of commonly compared wine regions (Table 4). For example, Burgundy, the Willamette Valley, and the Yarra Valley each grow similar varieties (Pinot noir and Chardonnay). However, while Burgundy and the Willamette Valley's median spatial climate values on all indices are similar on average, the Yarra Valley is significantly warmer. This result would be masked by a simple station comparison. Similarly, although Bordeaux, the Napa Valley, and Coonawarra are often compared, the results reveal that the Napa Valley is substantially warmer as a spatial average compared to Bordeaux and that Coonawarra is intermediate to Bordeaux and the Napa Valley. Furthermore, the five western U.S. locations (Table 4) all have greater within-region spatial variability on all climate indices than comparable locations in Europe or Australia (not shown), which are likely caused by greater elevation differences and the greater diurnal temperature ranges that result from lower humidity levels during the growing season (Jones et al. 2009).

While this research provides a detailed overview of the spatial characteristics of climate within the western U.S.

AVAs, the use of climate to describe and/or compare regions within the U.S. and worldwide is inadequate (McIntyre et al. 1987, McMaster and Wilhelm 1997). The numerous issues concerning the comparison of climate indices from other sources results from the historic use of station data, using data from different time periods, and using different methods of calculating the indices, especially degree-days (Moncur et al. 1989, Roltsch 1999, Cesaraccio et al. 2001, Battany 2009). While many governments and organizations recognize the 30-year climate normal period (1971–2000) as the standard (e.g., the World Meteorological Organization), not all published climate data (e.g., temperatures, degree-days) are summarized similarly. Some data may include the entire period of record (i.e., tens of years to over 100 years), while others might include a shorter subset of years. Using the same time period is important, as both climate variability and trends will result in changes in the statistical distribution of the data. For example, in the western U.S., GST and GDD have standard deviations of 0.7–1.2°C and 100–200 units, respectively (Jones and Goodrich 2008). However, the variability over differing time periods can vary by as much as 50% depending on the length of the data record. In addition, warming trends in GST and GDD in the western U.S. during 1948–2004 have been 0.9–1.7°C and 100–300 units, respectively, indicating the importance of using the exact same time period for climate index comparisons (Jones 2005, Jones and Goodrich 2008).

A comparison of the 1971–2000 time period spatial AVA results with the original map and data (Winkler et al. 1974, pages 62-66) reveals some significant differences due to the use of stations, the time period of the data, and the available mapping technology at the time. First, Winkler and colleagues used data from multiple sources without specifying the time period of the data or the exact method of calculation for the degree-days reported (i.e., simple average GDD, and daily, multiday, or monthly formulations), which makes precise comparisons difficult. Second, the use of individual stations and the construction of a map from the few sites in each region resulted in a general depiction of the climate in California at the time but with marginal accuracy. Broad areas were shown with similar levels of suitability, whereas the spatial data used in this research depicts much more pronounced within-region variation. Third, a sample of 30 stations (Winkler et al. 1974) reveals GDD values that are 160 GDD (10%) lower on average (ranging 3 to 23% lower) than their respective 1971–2000 station climate normals (Western Regional Climate Center; www.wrcc.dri.edu). Climate changes highlight the need to use values from a current and similar time period to more precisely compare wine region climates (Jones 2005).

Table 4 Wine region total area, median elevation, and median values for each of the climate indices for Europe (Jones et al. 2009), Australia (Hall and Jones 2010), and selected western U.S. AVAs from Tables 2 and 3. Climate indices are average growing season temperature (GST, °C), growing degree-days (GDD, C° units), Huglin index (HI, C° units), and biologically effective degree-days (BEDD, C° units). Table sorted by GST.

Location	Region	Area[a] (km²)	Elev (m)	GST (°C)	GDD	HI	BEDD
Germany	Mosel	198	179	14.0	891	1411	966
Germany	Rheinhessen	327	170	14.1	922	1473	989
France	Champagne	381	170	14.2	923	1492	981
Germany	Baden	189	245	14.9	1056	1602	1117
Oregon	Willamette Valley	13876	122	15.0	1081	1748	1195
France	Burgundy	260	264	15.2	1118	1648	1171
Italy	Valtellina Superiore	5	476	16.2	1335	1880	1304
France	Bordeaux	1471	50	16.5	1387	1890	1382
Spain	Rioja	605	506	16.6	1410	1886	1343
Australia	Coonawarra	400	65	16.9	1457	1998	1498
Washington, Oregon	Walla Walla	1306	317	17.1	1528	2296	1480
Australia	Yarra Valley	3120	251	17.3	1558	2000	1510
France	Côtes du Rhône Méridionales	1440	174	17.3	1570	2067	1447
Italy	Barolo	56	314	17.5	1600	1960	1559
Italy	Vino Nobile di Montepulciano	28	307	17.5	1613	2057	1473
Portugal	Vinho Verde	61	190	17.6	1635	1987	1576
Italy	Chianti Classico	101	321	17.9	1685	2112	1507
Portugal	Porto	807	437	17.9	1684	2155	1489
Australia	Barossa Valley	590	278	18.7	1848	2302	1670
Australia	Margaret River	2640	75	18.7	1844	2201	1676
California	Napa Valley	1624	248	18.8	1883	2504	1850
California	Paso Robles	2464	398	18.9	1903	2681	2032
Spain	La Mancha	2864	689	18.9	1912	2417	1445
California	Lodi	2195	24	20.3	2211	2797	1980
Spain	Jerez-Xéres-Sherry	126	57	20.9	2343	2441	1921

[a] Area rounded to the nearest 1 km² (100 ha); approximate due to resolution and precision of the wine region boundary data.

How data are averaged (i.e., hourly, daily, or monthly) is another issue in comparing climate information. While the advent of better weather station instrumentation and software to calculate climate indices has helped to develop site-specific data from hourly or shorter time periods, often this data is compared to historical information from daily maximum and minimum observations or monthly data. Hourly data, which arguably better reflects the true thermal effects on the crops, results in heat accumulation values that tend to be lower than both daily and monthly approximations (McIntyre et al. 1987, Battany 2009), while monthly data can slightly underestimate heat accumulation during the first and last months of the growing season (Gladstones 1992). Therefore, it is important to compare similar time period averaged data. Furthermore, the use of readily accessible daily maximum and minimum temperature data to derive heat accumulation values has been criticized for not representing the diurnal structure of temperature (Snyder et al. 1999, Roltsch et al. 1999, Cesaraccio et al. 2001). Various methods have been proposed (e.g., sine wave, triangle) to improve the simple averaging method and have achieved some success. However, these methods do not produce tremendous differences in heat accumulation indices that would affect general suitability studies for viticulture, are much more applicable for scientific field applications such as phenological modeling (Snyder et al. 1999), are not readily accessible for the average grapegrower, and are not comparable to commonly published climate index values.

Another significant methodological difference exists between simple average GDD formulations that are standard practice in viticulture studies (Winkler et al. 1974, Gladstones 1992, Jones 2006) and the so-called corn degree-days (McMaster and Wilhelm 1997). The main difference is how the base temperature is dealt with in the formula. With the simple average method, for any day with an average temperature below the base of 10°C for winegrapes, there is no accumulation. The corn degree-day method, however, adjusts all minimum temperatures to the base, therefore artificially adjusting the average temperature and resulting in spring and fall monthly values 50–400% higher than simple average degree-days or Apr–Oct total accumulations 28–33% higher (McMaster and Wilhelm 1997). According to calculations for a sample of western U.S. wine regions, the corn degree-day formulation was 10–15% higher than the simple average formulation (authors' unpublished data, 2009). Furthermore, while corn degree-days may be the standard for broadacre crops (McMaster and Wilhelm 1997), the formulation has a set upper limit of 30°C, which, along with artificially adjusting the base temperature, may or may not be appropriate for winegrapes (see below) and is not commonly applied in historic degree-day calculations for viticulture (Jones 2006). Furthermore, as the corn method has been integrated into some weather station software (e.g., HOBOware, Onset Computer Corporation), it can confound any comparison with published data using the simple average method.

While previous research has suggested that refinements to understanding wine region climate indices are needed (Winkler et al. 1974, McIntyre et al. 1987), no large-scale work in this area has been attempted. Optimizing the lower and upper temperature thresholds for degree-day formulations is one topic for additional research. While these thresholds have typically been defined by their influence on phenological event timing, they are commonly derived from photosynthetic activity limits. For example, it has been shown that very little photosynthesis occurs in grapevine leaves when temperatures are <5°C (Kriedemann 1968). Furthermore, while there is strong evidence for a 4°C base temperature for grapevines in Australia (Moncur et al. 1989) and a 5°C base from modeling efforts in France (García de Cortázar-Atauri et al. 2009), there has been little confirmation of these thresholds across other wine regions and for a wider range of varieties. In addition, from the discussion of early versus late budding varieties (Winkler et al. 1974), the base temperature threshold for accumulation is likely strongly cultivar specific. There is also some evidence that grapevines have a maximum temperature threshold of ~32 to 35°C (Jackson 2000), although others have found that optimum net photosynthesis occurs over a wide range of temperature (25–35°C), making it difficult to pinpoint a universal upper temperature threshold (Kriedemann 1968). The application of an upper threshold of 19°C (average temperature) to heat accumulation in the BEDD formulation attempted to quantify this issue (Gladstones 1992), but was identified by trial and error and needs further examination.

Two important issues involved in the clasification of quantitative data include the number of classes and the specific way the data is divided into the classes. Such determinations are important for depicting climate indices for viticulture suitability because they can include or exclude sites/regions and are often based on convenience (i.e., rounded numbers). For example, Amerine and Winkler (1944) specified their five region concept in order to "reduce the size of the tables and differentiate among the recommendations," not necessarily to provide clear demarcations between climate-class suitability. In addition, the specified classes did not assign specific lower and upper limits to Regions I and V, respectively, but only noted approximate limits of 950 and 2778 based on anecdotal evidence from a short list of climate stations worldwide, not stations in the western U.S. or California. In this work, a lower limit of 850 GDD (WI Region I) was applied based on inclusion of the median GDD of the coolest region, the Puget Sound AVA. The validity of this limit is evidenced by trial planting and commercial vineyard observations in the Puget Sound AVA (Moulton and King 2006). However, a criticism of the Winkler region divisions (Gladstones 1992, Jones 2006) is that it does not discriminate sufficiently between cooler climate zones (Region I), indicating that the range from 850 to 1389 should be subdivided into two or more classes. We have also applied an upper limit of 2700 GDD (Region V) based on the spatial climate characteristics of the Madera AVA, the warmest region in the western U.S. Finally, the class limits applied to climate indices should considered general demarcations between broad regions or maturity groups, whereby some varieties clearly overlap from one class type to another (e.g., GST maturity classes; Jones 2006).

Other potential climate index criteria have been developed. Recent research that shows promise for viticulture suitability depiction combined a reduced number of climatic indices that account for solar, frost, and drought variability and provided a classification of viticulture climates (Tonietto and Carbonneau 2004). This Multicriteria Climatic Classification system (Geoviticulture MCC) results in 36 different climatic types from a summation of three indices; the Huglin index, a cool night index, and a dryness index. The classification has been successfully tested to differentiate the climate of 97 stations in wine regions worldwide. However, the complex comparison of station versus regionwide spatial climate is evident even in the MCC system (Tonietto and Carbonneau 2004), whereby the given values are often warmer (urban stations) than the actual wine region median index values (Jones et al. 2009). However, the MCC system has been applied to numerous climate stations in the Galicia region of Spain, effectively portraying the spatial climate suitability for Galicia (Blanco-Ward et al. 2007). The indices of the MCC system were also spatially modeled over Europe (Jones et al. 2009). However, the application of the MCC system is limited because the dryness index requires long-term observations on potential evapotranspiration and soil conditions, which are not available from all climate stations or well represented in spatial climate data products. Furthermore, the cool night index class structure does not appear universally valid, especially for the western U.S. where lower ripening period nighttime temperatures and higher diurnal temperature ranges are experienced (Jones et al. 2009).

Conclusions

Establishing a region's spatial climate characteristics and suitability for viticulture provides researchers, growers, and wine producers with information to compare wine region climates. However, published climate information is often tied to individual stations, which do not represent the true spatial climate characteristics within any wine region. In addition, comparative climate information is often published without documentation of the time period it represents and how the climate index was formulated, resulting in erroneous comparisons. Furthermore, little has been done to update the original formulation of suitable climate zones for viticulture in California. This research has updated and depicted the climate for viticulture over the western U.S. AVAs using recently available higher resolution and spatially validated climate grids over a common time period (1971–2000 climate normals). In addition, the research provides for the first time a regionwide comparison of four climate indices historically used in various regions worldwide. The research describes the spatial framework of the climate indices over the wine regions (AVAs) instead of the common method of station-to-station comparison.

Results show that each climate parameter depicts a broad structure across a range of cool to hot climates suitable for viticulture in western U.S. AVAs. Comparison of GST and GDD indices reveals no functional differences, except in terms of magnitude. While GDD is useful for determining stages of annual phenological development at time steps within a season, GST is simpler to calculate, has fewer methodological issues, and provides a similar comparative result over the whole season. The HI and BEDD indices both provide good AVA-wide depictions of known climate suitability, owing to a latitude adjustment for increasing day lengths poleward, at the expense of either excluding known suitable regions or including areas that may or may not be climatically viable. Furthermore, the HI and BEDD appear to better differentiate the within-AVA structure of the climate indices, with BEDD showing the greatest promise because of its diurnal temperature range adjustment and its tie to variety maturity classes. However, both the HI and BEDD need further validation for use in the western U.S.

Developments in spatial climate data products have allowed for the depiction and assessment of climate characteristics by accounting for climate variations over the landscape. While microscale site differences are still not fully depicted in our spatial climate data, the ~400 m resolution of the PRISM data provides a substantial improvement in understanding general site climate characteristics. Its application as a statistical range over wine regions allows for a better assessment of the spatial climate characteristics within them. While this work does not fully account for the potential shortcomings of heat summation formulations, it addresses some concerns and provides the framework for future assessments and refinements. First, it is suggested that users of climate data for comparing wine regions know the lineage of the published numbers or data (e.g., source, time period of data summary, and whether formulations are hourly, daily or monthly). Additionally, it is important that researchers, software developers, and others clearly communicate the method of calculating growing degree-days so that others can correctly interpret and compare results. If corn degree-days or some other nonviticulture standard formulation is implemented in the weather station software, a user should export the raw daily data to a spreadsheet to calculate the degree-days.

While the temperature-based climate indices examined here have been developed with consideration of viticultural suitability, the applicability of the indices to wine regions outside of where they were originally developed has not been fully examined. The data and methods presented here and by others using spatial data products are providing a more holistic look at climate index characteristics for viticulture globally and the framework by which regional validation can be further examined. However, as greater spatial resolution of the climate grids and new time periods of data (i.e., 1981–2010 climate normals) become available, this work should be updated so that climate suitability, variability, and change are monitored and reported appropriately.

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