ANALYSIS OF VITICULTURE REGION CLIMATE STRUCTURE AND SUITABILITY IN NEW ZEALAND

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Abstract

Aims: This research analyzes four climate indices derived from gridded, interpolated data to assess New Zealand's climate structure and variation among wine regions.

Methods and results: High resolution gridded data based on 1971-2000 climate normals was used to characterize climate indices depicting viticultural suitability in a geographic information system. The statistical properties of each index were assessed over 21 New Zealand viticulture regions. The results show predominately cool to moderately warm climate suitability in New Zealand, comparable to many European and United States regions. While many viticulture regions have one primary class of suitability, variability of climate within regions can be significant, with some regions containing two to four climate classes, making them suitable for a greater range of cultivars.

Conclusion: While the indices depict broad patterns expected over New Zealand, both within and between region variations can be substantial among the indices. However, two indices, Growing Season Average Temperature (GST) and Growing Degree-Days (GDD), are functionally identical, but GST is easier to calculate and overcomes many methodological issues in GDD.

Significance and impact of the study: This research provides the basis for evaluating general suitability for viticulture in New Zealand, assists comparisons between viticulture regions in New Zealand and worldwide, and offers growers measures of assessing appropriate cultivars and sites.

Key words: climate, degree-days, New Zealand, temperature, viticulture

Résumé

Buts: Ce travail analyse quatre indices climatiques provenant de données maillées et interpolées afin d'évaluer la structure climatique de la Nouvelle-Zélande et la variation entre les régions viticoles.

Méthodes et résultats: Des données maillées à haute résolution basées sur les normales climatiques de 1971-2000 ont été utilisées pour caractériser les indices climatiques représentant la pertinence viticole dans un système d'information géographique. Les propriétés statistiques de chaque indice ont été évaluées sur 21 régions viticoles de Nouvelle-Zélande. Les résultats montrent une situation climatique essentiellement fraîche à modérément chaude en Nouvelle-Zélande, ce qui est comparable à plusieurs régions européennes et américaines. Alors que beaucoup de régions viticoles ont une seule classe de climat approprié, la variabilité climatique dans les régions peut être significative, avec des régions comportant deux à quatre catégories de climat, qui conviennent à un grand nombre de cépages.

Conclusion: Même si les indices définissent de grandes tendances en Nouvelle-Zélande, les variations à l'intérieur et entre les régions peuvent être considérables. Toutefois, deux indices, la température moyenne de la période de végétation (GST) et les degrés-jours (GDD) de croissance sont fonctionnellement identiques, mais la GST est plus facile à calculer et compense plusieurs questions méthodologiques en GDD.

Signification and impact de l'étude: Cette recherche donne des bases pour évaluer la pertinence de la viticulture en Nouvelle-Zélande, permettre des comparaisons entre les régions viticoles de Nouvelle-Zélande et du Monde entier et offrir aux viticulteurs des mesures d'évaluation de l'adéquation des cépages cultivés et des lieux de production.

Mots clés: climat, degrés-jours, Nouvelle-Zélande, température, viticulture

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INTRODUCTION

Growing any crop to high quality and to economically sustainable standards anywhere in the world is strongly dependent on climate (Rosenzweig and Hillel, 2008). While some crops have more broad geographic and, therefore, climatic zones where they can adequately grow, ripen, and produce high quality products (e.g., corn, rice, soybeans, etc.), others have more narrow zones for optimum suitability (e.g., potatoes, sugar cane, pears, etc.). Combined, both table and wine grapes are the fifth highest value crop worldwide (FAO, 2011) yet are grown in relatively narrow geographic and climatic zones (Jones, 2006). Grapes are highly sensitive to their climatic environment, being largely driven by suitable temperature and precipitation regimes (Becker, 1985). However, while many factors other than temperature drive viticultural suitability and wine production (Jackson and Lombard, 1993 ; Jones and Davis, 2000 ; Jackson and Schuster, 2001), simple to complex indices of temperature are the most common measures used to assess what types of grapes can be grown in which climates (Jones *et al.*, 2010). For example, simple growing season average temperatures (April through October in the Northern Hemisphere and October through April in the Southern Hemisphere) have been used to put upper and lower limits on suitability worldwide (Jones, 2006). Grapes can be grown successfully in areas with growing season average temperatures that range from 13 to 24 °C, with winegrapes being limited to the 13-21 °C range, and table grapes and fortified wines typically to the 21-24 °C range (Gladstones, 1992 ; Jones, 2006). For winegrapes, this range corresponds to the suitability of cultivars across cool, intermediate, warm, hot, and very hot climates, with most cultivars having a climate niche of 3 °C or less for optimum production and quality (Jones, 2006). For example, while cool climate cultivars (e.g., Pinot noir) can be grown in warmer climates, the climatic conditions do not allow for the development of the desirable balance in the various primary and secondary metabolites to make a recognized wine style and quality for that cultivar. Other temperature-based climate measures in viticulture suitability studies typically account for either simple temperature characteristics such as the mean temperature of the warmest month (Smart and Dry, 1980), heat accumulation or growing degree-day formulations that include moisture or solar radiation parameters (Amerine and Winkler, 1944 ; Branas, 1974 ; Huglin, 1978 ; Riou *et al.*, 1994 ; Winkler *et al.*, 1974 ; Fregoni, 2003), latitude-temperature indices (Kenny and Shao, 1992), or multi-parameter or multi-index methods that use combinations of temperature, relative humidity, sunshine hours, evapotranspiration, and continentality (Smart and Dry, 1980 ; Tonietto and Carbonneau, 2004).

Historically, wine producing regions have been compared using simple station to station values of temperature, which typically do not represent the actual vineyard areas in the vicinity of the stations (Gladstones, 1992). Today, gridded climate products have been developed to overcome this issue, providing robust, validated, and more spatially appropriate climate data (Thornton *et al.*, 1997 ; Hijmans *et al.*, 2005 ; Daly *et al.*, 2008). Using gridded climate data sets, previous studies have examined viticulture region climate characteristics in Europe (Jones *et al.*, 2009), the United States (Jones *et al.*, 2010), and Australia (Webb *et al.*, 2007 ; Hall and Jones, 2010) and have provided more holistic measures to help understand the range of cultivar suitability within viticulture regions. For example, Bordeaux and Napa Valley grow similar cultivars, produce similar wines, and are often mentioned as climatically similar wine producing areas ; however, station comparisons mask the overall regional differences in the two regions. Jones *et al.* (2009) examined the spatial climate characteristics for these two regions and found that the Napa Valley is overall substantially warmer than Bordeaux and also has greater within region variation in climates for winegrape production. Developing more studies such as those described above for other viticulture regions will provide a greater understanding of their spatial climate characteristics and how these geographically diverse areas compare to other regions worldwide.

New Zealand has become one of the world's most recognized cool climate growing regions. Initially, the development of viticulture in New Zealand was slow due to cultivar-climate mismatches and low demand for wine in the marketplace (Sluys, 2006). However, since the 1970s, New Zealand experienced rapid expansion and growth in its wine industry, and during the 1980s and 1990s, the country saw a shift to export markets, resulting in strong growth that continues today. The initial plantings of grapevines in New Zealand included a range of cultivars, but the matching of appropriate cultivars to climate and the management of the vines largely reflects the success of specific wine styles in the international marketplace. As of 2008, New Zealand was the 22nd highest wine producing country in the world (The Wine Institute, 2011) and one of the few experiencing growth, with acreage, production, and export value increasing nearly seven-fold from 1999 to 2009 (NZWine, 2009).

New Zealand grows over 50 cultivars, with a cultivar ratio of approximately 75 : 25 white to red, the top cultivars of which are Sauvignon blanc (~51 % of the country's total production) and Pinot Noir (~15 %), respectively (NZWine 2009). However, strong regional differences in cultivars grown across wine regions are evident (e.g., Marlborough is ~75 % Sauvignon blanc, Gisborne is ~53 % Chardonnay, Hawkes Bay ~30 % Merlot and Cabernet-Sauvignon, and Otago is ~79 % Pinot Noir). In 2009, New Zealand supported 1128 growers, nearly 32000 bearing hectares, 645 wineries, and crushed 285000 tons of grapes, producing 205 million liters of wine with an export value near one billion NZ$ (NZWine, 2009).

New Zealand has ten main wine growing areas (Figure 1) that extend roughly 1100 km from Northland (~35°S) to the world's most southerly wine growing area, Central Otago (~45°S). Although this latitudinal zone is roughly equivalent to United States and European wine regions such as Paso Robles, California or Jerez, Spain (35.5-36.5°N) and the Willamette Valley, Oregon or Bordeaux, France (45-46°N), New Zealand has a much more pronounced maritime climate than comparable latitudes on the North American and European continents. Being surrounded by water, New Zealand's climate is strongly moderated, with cooler summers and milder winters than would be expected at similar latitudes in Europe and North America. The maritime influence is accentuated by the proximity of the vineyard areas to the east coast, with approximately 95 % of the vineyards in these areas planted within about 50 km of the coast, the exception being Central Otago. Furthermore, while portions of western New Zealand experience very high annual precipitation, most of the wine producing regions are situated in the rain shadows to the east (Figure 1).

While a good deal of research has been done to understand the way New Zealand's climate influences winegrape growing (Jackson and

Figure 1 - New Zealand viticulture and wine producing regions. The larger regions are delineated by the bold, dashed lines and the viticulture and wine region boundaries used in the analysis are given in solid gray.

Schuster, 2001), much of the work has focused on comparing regions using station or individual research site data (Jackson and Cherry, 1988 ; Tesic *et al.*, 2002 ; Tonietto and Carbonneau, 2004). Therefore, the purpose of this research is to examine commonly used temperature-based indices to assess the spatial characteristics of climate in New Zealand wine producing regions. The work utilizes gridded climate data and wine region boundaries to develop spatial climate indices for New Zealand so that more appropriate characterizations of these regions and comparisons with others worldwide can be made.

MATERIALS AND ANALYTICAL METHODS

1. New Zealand wine growing region mapping

To assess the spatial characteristics of viticulture regions in New Zealand, boundaries of the producing areas were needed. Many viticulture regions worldwide have government approved appellation areas such as the Appellation d'Origine Contrôlée system in France, American Viticultural Areas in the United States, Wine of Origin Wards in South Africa, and Geographical Indications in Australia. However, New Zealand has not officially designated its viticulture regions but has implemented the Geographical Indications (Wines & Spirits) Act of 2006 by which Geographical Indicator (GI) zones, regions, and sub-regions are in various stages of being formally mapped and recognized (New Zealand Winegrowers, http://www.nzwine.com/ accessed January 2011). For this research, we estimated the viticulture regions via published data on vineyard locations (developed by Tait 2005 from Land Information New Zealand (LINZ) and the Land Cover Database (LCDB)), preliminary boundaries created by some of the regions, recent aerial imagery, and digital elevation data. Boundaries were drawn around the general areas of vineyards and are only estimates with the understanding that the formal GIs will likely vary from those used in this research. Furthermore, while New Zealand has ten broad viticulture and wine producing zones (Figure 1), within each of these zones there are more defined regions or sub-regions where vineyards are established (Tait, 2005). Since our approach was to examine the climates at the region and sub-region scales, our boundaries represent 21 mapped wine growing areas (Figure 1).

2. Temperature grids

In order to accurately calculate and analyze temperature-based climate indices for this research, National Institute of Water and Atmospheric Research (NIWA) grids containing values for average daily maximum and minimum temperatures at a spatial resolution of 500 m for the months of October through April for all of New Zealand were used (Tait, 2005 ; Tait *et al.*, 2006 ; Tait and Zheng, 2007 ; Tait, 2008). The grids are based on daily data collected from climate stations across New Zealand for the period 1971-2000 (Wratt *et al.*, 2006). As individual weather stations can only record information at their specific sites, the grids were created with a second order derivative trivariate thin plate smoothing spline model using latitude, longitude and elevation to interpolate the temperature data from the irregularly spaced climate stations onto the high resolution (500 m by 500 m) regular grids (Wratt *et al.*, 2006). The annual and seasonal temperature grids have been shown to have root mean square errors of 0.3-0.5 °C for individual climate stations, which is in a similar range to gridded data created and used in Australia (Tait and Zheng, 2007 ; Hall and Jones, 2010). These temperature grids, along with other climate parameter grids, have been used in flood zone estimation, in finding potential wind power generating sites, and in developing suitability maps for growing winegrapes in New Zealand (Tait, 2005).

3. Climate indices

The average daily maximum and minimum temperature grids were then used to derive four climate indices for New Zealand : a growing season average temperature index (GST), standard growing degree-days (GDD) as represented in the Winkler Index (WI), the Huglin Index (HI), and a biologically effective degree-day index (BEDD). These indices were selected based on their previous use and acceptance in understanding climate characteristics favorable for specific winegrape cultivars and the general wine style that can be produced within a given climate (Jones *et al.*, 2010).

The GST index was calculated by determining the average temperature for the seven growing season months (October through April). The calculated values were then categorized into five classes using designations of cool, intermediate, warm, hot, and very hot, with values ranging from 13 °C to 24 °C (Table 1). The GST index can be used broadly to categorize winegrape growing regions based on maturity potential or climate suitability in addition to delineating maximum and minimum latitudes for viticulture (Jones, 2006 ; Jones *et al.*, 2010).

Table 1 - Derived climate variables and the median index classification frequencies of the New Zealand wine regions.

Variable	Equation	Months	Class Limits†	Count	Frequency
Growing Season Average Temperature (GST)	$\frac{\sum_{d=1}^{n}[T_{max}+T_{min}]/2}{n}$	1 October - 30 April	Too Cool < 13°C	0	0
			Cool = 13-15°C	5	24
			Intermediate = 15-17°C	10	48
			Warm = 17-19°C	6	29
			Hot = 19-21°C	0	0
			Very Hot = 21-24°C	0	0
			Too Hot > 24°C	0	0
Growing Degree-Days (GDD)‡	$\sum_{d=1}^{n}\max[(T_{max}+T_{min})/2-10,0]$	1 October - 30 April	Too Cool < 850	2	10
			(Region Ia) 850-1111	6	29
			(Region Ib) 1111-1389	4	19
			(Region II) 1389-1667	9	43
			(Region III) 1667-1944	0	0
			(Region IV) 1944-2222	0	0
			(Region V) 2222-2700	0	0
			Too Hot > 2700	0	0
Huglin Index (HI)	$\sum_{d=1}^{n}\max[(T_{mean}-10+T_{max}-10)/2,\ 0]K$ where K is an adjustment for latitude/day length§	1 October - 31 March	Too Cool < 1200	1	5
			Very Cool = 1200-1500	6	29
			Cool = 1500-1800	12	57
			Temperate = 1800-2100	2	10
			Warm Temperate = 2100-2400	0	0
			Warm = 2400-2700	0	0
			Very Warm = 2700-3000	0	0
			Too Hot > 3000	0	0
Biologically Effective Degree-Days (BEDD)	$\sum_{d=1}^{n}\min[\max([T_{max}+T_{min}]/2-10,0)K+DTR_{adj},9^{\#}]$ where $DTR_{adj}=\begin{cases}0.25[DTR-13], & [DTR]>13\\ 0, & 10<[DTR]<13\\ 0.25[DTR-10], & [DTR]<10\end{cases}$ DTR_{adj} is an adjustment for diurnal temperature range and K is an adjustment for latitude/day length§	1 October - 30 April	< 1000	3	14
			1000-1200	6	29
			1200-1400	5	24
			1400-1600	7	33
			1600-1800	0	0
			1800-2000	0	0
			> 2000	0	0

† Note that the class names given in the table are not directly comparable (e.g., GST cool does not necessarily compare to HI cool).
‡ Note that the GDD classes are based upon rounded °F limits as defined by Winkler et al. (1974) (in parentheses), which produce non-rounded classes in °C units.
§ K is a latitude coefficient that takes into account increasing day lengths starting from 1.0 at 34° increasing incrementally pole ward and is based upon day lengths using Julian day and latitude.
# Note that the BEDD calculation has a lower limit 10 °C and upper limit 19 °C, resulting in 9°C maximum as shown in the equation.

GDDs were calculated using the standard formula (Table 1) with a base temperature of 10 °C (below which winegrape growth is assumed to be negligible), no upper cut-off, and summing the daily values over the October through April months. For this research, the standard Winkler regions (Winkler *et al.*, 1974) were used to determine the class designation of each cell ; however, the original index method did not place lower or upper bounds on the coolest and warmest classes. Therefore, two additional limits determined by Jones *et al.* (2010) in the western US and used by Hall and Jones (2010) in Australia were added : a lower threshold of 850 GDD and an upper threshold of 2700 GDD (Table 1). Furthermore, the lower WI Region I class is sub-divided into Region Ia (850-1111) and Region Ib (1111-1389) to help differentiate cool climate regions and provide roughly equivalent class widths to the other region categories, totaling six classes (Table 1).

The HI was calculated similarly to GDD but includes in its calculation a stronger weighting for maximum temperature (subtracting the base temperature from both the maximum and the mean prior to averaging ; Table 1) and an adjustment to each cell based on the length of the day at its latitude (Huglin, 1978). While the original latitude adjustment was applied only across latitudes of European wine producing areas, Hall and Jones (2010) and Jones *et al.* (2010) have updated the formula for all latitudes. Additionally, Huglin's calculation, when used for locations in the Northern Hemisphere, uses six months from April through September, leaving off October as he suggested that harvesting during that time rendered the values less important (Jones *et al.*, 2010). In order to remain consistent with other studies, this research uses a six month growing season for the HI running from October through March. Furthermore, the calculated values were placed in eight class categories that range from too cool, being less than 1200, to too hot, being greater than 3000 (Table 1).

The BEDD index was calculated in a similar manner to both the HI and WI but uses a formula that assumes potential plant growth is not linear at all temperatures (Gladstones, 1992). Like GDDs, the BEDD index assumes a minimum base value for plant growth (10 °C) but also places an upper threshold on temperature (19 °C), beyond which significant additional growth potential is unlikely

Table 2 - Statistics for the elevation and overall area of land in the New Zealand viticulture regions depicted in Figure 1 (Source : Geographx, 2010).

Wine Region	Area (km^2)	Elevation (m)			
		Median	Max	Min	Range
Awatere Valley	239.1	118	428	0	428
Bay of Islands	465.0	52	411	0	411
Bay of Plenty	1821.2	184	830	0	830
Christchurch	2234.1	50	803	0	803
Clevedon	204.2	77	461	0	461
Gisborne	227.7	21	320	5	315
Hawkes Bay	599.0	29	266	0	266
Henderson	5.9	26	61	18	43
Kaitaia	8.3	19	85	9	76
Kumeu	52.4	36	125	0	125
Lake Rotorua	88.7	310	680	283	397
Martinborough	290.2	104	633	7	626
Matakana	101.6	25	141	0	141
Nelson	308.2	34	261	0	261
Otago	1089.0	340	1380	135	1245
South Canterbury	253.5	115	453	19	434
Waiheke Island	91.9	51	220	0	220
Waikato	877.5	40	440	16	424
Waipara Valley	268.6	139	548	35	513
Wairau Valley	610.8	80	520	0	520
Whangarei	140.9	82	342	0	342

(Table 1). And, like the HI, the BEDD index uses an adjustment to account for day length at varying latitudes. In addition, the BEDD index also includes an adjustment based on the daily temperature range (upward if the temperature is greater than 13 °C and downward if it is less than 10 °C). The values were assigned to five classes (Table 1) as used in similar research (Hall and Jones, 2010; Jones *et al.*, 2010).

After combining the spatial boundaries of the viticulture regions, elevation data (100 m digital elevation grids; Geographx, 2010) and climate index grids, we then characterized the area, elevation, and climate of each region with summary statistics. For the climate indices, quantile statistics (minimum, 25 %, median, 75 % and maximum) representing each climate index grid in each region were calculated to give a spatial representation of the climate measures over the whole region.

RESULTS

The 21 viticulture regions represent nearly 10000 km^2 of area with the largest being Christchurch and the Bay of Plenty regions and the smallest being the Henderson and Kaitaia regions (Figure 1 and Table 2). However, note that vineyards are not planted over the entire extent of these regions; therefore, a large area in Table 2 does not mean a higher proportion of planted vineyards. For example, in 2009, the Marlborough wine producing area (Wairau and Awatere valleys) had 19295 ha planted while the Canterbury wine producing area (Christchurch/Waipara Valley) had only 1779 ha planted (NZWine, 2009). Furthermore, while vineyards are not present at all elevations within the regions, the elevation statistics (Table 2) provide a guide to the range of climates available within each region. The average elevation across the 21 regions is just less than 100 m, with maximum elevations found in the Otago region and minimum elevations at sea level in many regions. In addition, Otago has the highest range in elevations, while Henderson and Kaitaia have the lowest elevation ranges.

Over the entire country, a complete grid cell analysis shows that the climate indices are highly correlated ($0.96 < r < 0.99$). The BEDD and GDD indices exhibit the strongest correlation, while HI and GDD exhibit slightly weaker correlation (not

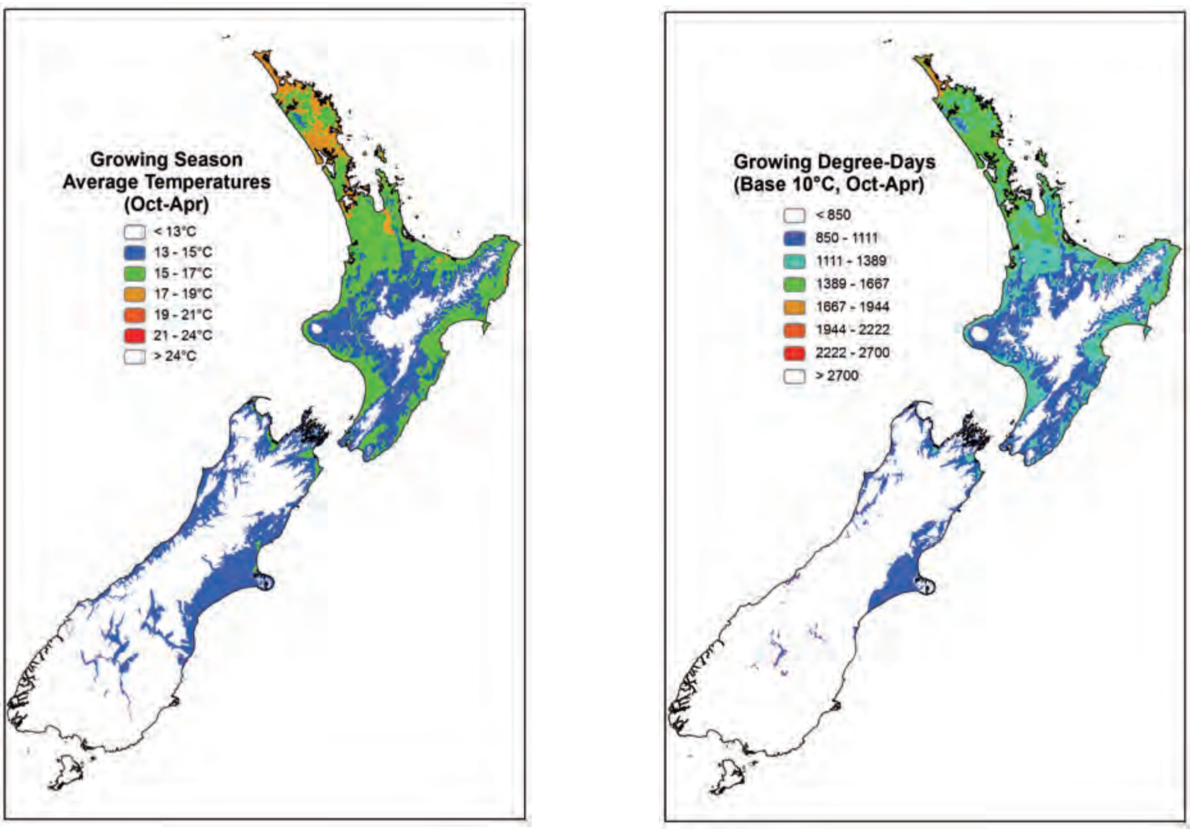

Figure 2 - Maps of growing season average temperatures (GST, left panel) and growing degree-days (GDD, right panel), over the New Zealand wine regions as derived from the NIWA 1971-2000 gridded climate normals. Both variables are mapped according to the classes given in Table 1.

Table 3 - Quantile statistics for New Zealand viticulture regions calculated from 500 meter temperature grid data for growing season average temperature (GST) in °C, growing degree-days (GDD), Huglin Index (HI) and biologically effective degree-days (BEDD) in C° units sorted by median GST. (Gridded Data Source : Tait 2008)

Wine Region	GST (°C)					GDD (C° units)					HI (C° units)					BEDD (C° units)				
	Min	25%	Median	75%	Max	Min	25%	Median	75%	Max	Min	25%	Median	75%	Max	Min	25%	Median	75%	Max
South Canterbury	12.1	13.1	13.2	13.6	14.0	465	655	678	755	849	948	1109	1187	1285	1386	483	670	700	784	880
Otago	9.1	13.0	13.8	14.2	14.8	126	647	805	878	1022	446	1217	1402	1497	1624	100	672	841	925	1065
Christchurch	11.6	13.8	14.3	14.5	15.1	403	797	904	959	1080	746	1307	1385	1432	1475	305	823	929	989	1087
Waipara Valley	13.2	14.3	14.7	15.0	15.2	683	913	993	1055	1097	1195	1425	1499	1546	1594	703	940	1024	1087	1131
Awatere Valley	14.0	14.7	14.8	15.0	15.4	848	985	1023	1058	1136	1264	1408	1435	1456	1487	849	1001	1034	1061	1112
Martinborough	13.0	14.6	15.0	15.3	15.5	622	969	1064	1122	1169	986	1372	1474	1539	1601	547	975	1083	1145	1197
Wairau Valley	13.4	14.8	15.1	15.3	15.6	721	1010	1068	1127	1184	1178	1498	1533	1572	1617	740	1035	1094	1152	1213
Nelson	14.4	15.1	15.2	15.5	15.8	921	1070	1101	1155	1222	1303	1474	1508	1533	1566	914	1088	1122	1156	1222
Lake Rotorua	13.9	15.1	15.3	15.5	15.6	818	1074	1128	1157	1186	1192	1432	1483	1509	1530	783	1061	1119	1150	1176
Bay of Plenty	13.1	15.0	15.8	16.4	17.2	671	1065	1220	1350	1516	985	1381	1550	1677	1786	564	1020	1203	1346	1468
Hawkes Bay	15.0	16.0	16.3	16.5	16.7	1066	1270	1334	1367	1423	1521	1702	1732	1757	1783	1086	1294	1358	1389	1431
Waikato	14.9	16.2	16.4	16.5	16.8	1030	1320	1350	1377	1430	1418	1700	1712	1722	1766	1038	1336	1361	1386	1427
Gisborne	15.5	16.4	16.6	16.7	16.8	1159	1355	1390	1411	1443	1553	1736	1761	1785	1803	1172	1375	1411	1433	1462
Clevedon	14.6	16.3	16.6	16.8	17.3	960	1322	1400	1441	1543	1284	1605	1674	1719	1762	911	1285	1364	1412	1448
Kumeu	16.3	16.6	16.6	16.7	17.0	1337	1390	1401	1414	1471	1621	1674	1688	1698	1734	1310	1371	1386	1396	1437
Whangarei	16.0	16.6	17.0	17.5	18.0	1268	1403	1489	1592	1684	1589	1708	1756	1838	1895	1259	1396	1447	1517	1564
Henderson	17.1	17.2	17.2	17.2	17.3	1498	1521	1529	1533	1550	1768	1783	1786	1788	1795	1465	1476	1479	1481	1488
Waiheke Island	17.0	17.3	17.4	17.6	17.8	1479	1539	1574	1601	1655	1612	1698	1737	1754	1782	1297	1379	1414	1432	1459
Matakana	17.0	17.3	17.5	17.6	17.8	1473	1545	1578	1607	1657	1618	1707	1727	1737	1759	1317	1405	1418	1429	1447
Bay of Islands	16.6	17.4	17.6	17.8	18.0	1391	1562	1606	1639	1694	1601	1795	1827	1852	1903	1299	1494	1521	1542	1582
Kaitaia	17.7	17.8	17.9	17.9	18.0	1639	1660	1663	1668	1684	1833	1861	1866	1869	1876	1530	1549	1552	1554	1556

shown). As expected, the GST values indicate warmer conditions over the North Island and cooler conditions over the South Island (Figure 2). Mapped GST indicate large areas of New Zealand are too cool to effectively sustain commercial viticulture, but substantial areas were classed as being suitable for cool, intermediate, and warm climate winegrape cultivars. The North Island contains areas that classed as too cool, cool (particularly inland and at elevation), intermediate, and warm (in the far north) (Figure 2). Most of the South Island was classed as too cool but has zones of cool climate suitability in numerous locations and some intermediate climate suitability in the Nelson, Wairau Valley, Awatere Valley, and Waipara regions. Summarizing the GST over the 21 regions finds that their average is 15.9 °C with median values ranging from 13.2 °C in South Canterbury to 17.9 °C in Kaitaia, or from cool to warm climate suitability (Table 3). Overall, the median values for the regions show that 48 % fall into the intermediate class, with 24 % and 29 % in the cool and warm classes, respectively (Table 1). The region with the coolest minimum GST is Otago, which is due to its higher latitude and the higher elevations found in the region (Table 2). The region with the highest minimum GST cells is Kaitaia, which also has a very low quantile range (0.3 °C) due to its smaller size.

Mapping GDDs for the growing season over all of New Zealand shows a similar spatial framework to the GST, although the GDD classes do not capture as many of the cool to intermediate climate zones on the South Island. However, the GDD classes differentiate within regions better than GST (Figure 2 ; Table 3). For the 21 regions, GDD averages 1252, with a wide range from 126 GDD in the higher elevations of Otago to 1694 GDD in the Bay of Islands (Table 3). The lowest median GDD value is found in the South Canterbury region (678), while the warmest median GDD is found in Kaitaia (1663). The region median GDDs result in 43 % being classed into WI Region II, 29 % in WI

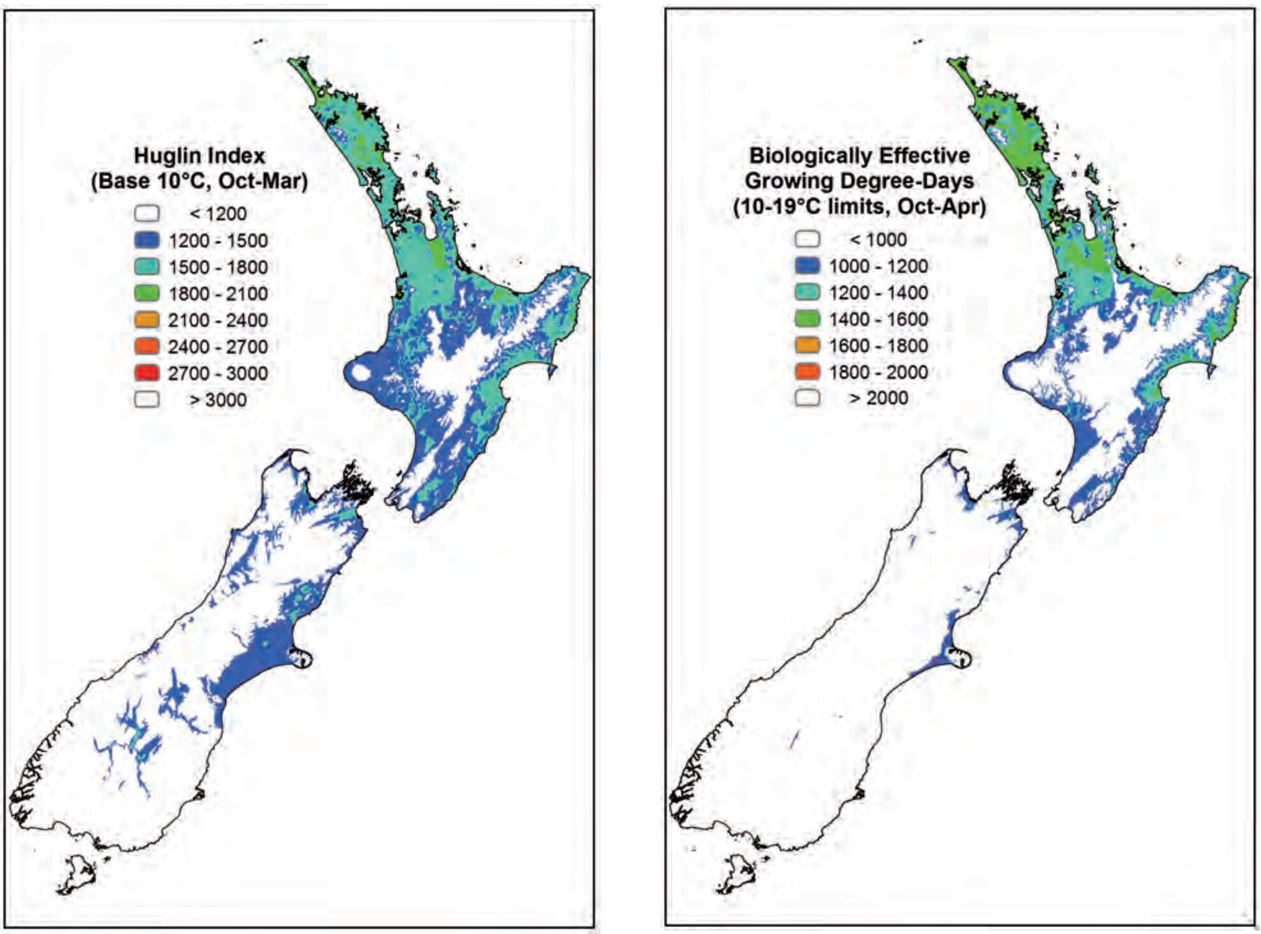

Figure 3 - Maps of the Huglin Index (HI, left panel) and biologically effective growing degree-days (BEDD, right panel), over the New Zealand wine regions as derived from the NIWA 1971-2000 gridded normals. Both variables are mapped according to the classes given in Table 1.

Region Ia, and 19 % in WI Region Ib (Table 1). Two areas, South Canterbury and Otago, were classed as too cool using the WI (< 850 GDD), but the results are skewed to the cool side due to large areas of these regions being at high elevations (see below).

The HI indicated very cool to temperate viticulture-climate structure over most of New Zealand (Figure 3). Temperate zones were only indicated as being present in the North Island, while the distribution of very cool and cool zones were comparable to those seen in the GST and GDD analyses (Figure 2). However, the HI tends to depict greater spatial homogeneity in climate classes than does the GST. Similar to the results for the GDD (WI Regions), the HI exhibits a wide range from the coolest areas of the higher elevation zones of Otago (446) to the warmest areas in the Bay of Islands (1903). The HI has an average value of 1606 across the 21 regions, with the lowest median in the South Canterbury region (1187) to the highest median in the Kaitaia region (Table 3). The distribution of the HI median values shows that 57 % of the regions were classed as ‘cool’ climate zones, while two regions are classed ‘temperate’, six ‘very cool’ (29%), and one just below the lowest threshold (South Canterbury; Table 1).

Most of the North Island was classified into the second and third coolest classes of the BEDD, with cooler classes near the coast in the southern portion of the island, and areas were classified as too cool at higher elevations (Figure 3). For the South Island, the BEDD is more indicative of limited suitability for viticulture than the other three indices, with only small areas of Otago and Christchurch in the coolest category and a few small areas in Nelson and Wairau reaching the second coolest category (Figure 3). The BEDD captures similar spatial characteristics to the other indices, with 24 % to 33 % of the median values of the viticulture regions falling in the cooler three categories (Table 1). Furthermore, the BEDD median values place three of the regions (South Canterbury, Otago, and Christchurch) below the coolest category, i. e., more than half of each of these regions were classified as too cool for sustained commercial viticulture. Overall, the average BEDD value across all regions was determined as 1231 (second coolest category) with a range from 700 (classed too cool) in South Canterbury to 1522 in Kaitaia (reaching the third warmest category of the BEDD) (Table 3).

A comparison of the median viticulture-climate index values reveals that they are highly correlated

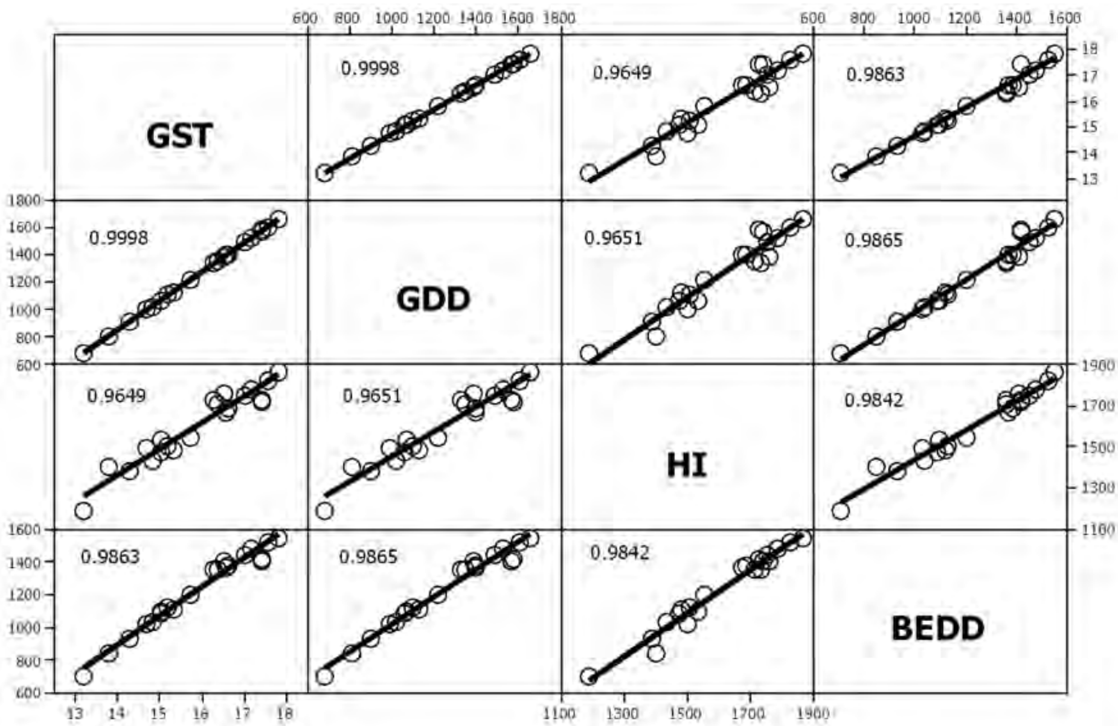

Figure 4 - Matrix scatterplot and Pearson correlation coefficients illustrating the relationships of the median wine region values for the growing season average temperature (GST), growing degree-days (GDD), Huglin (HI) and biologically effective degree-days (BEDD) indices. Each plotted point represents one wine region.

Table 4 - Wine producing region total area and spatial median values for elevation and climate indices for Europe over 1950-2000 (Jones et al. 2009), Australia for 1971-2000 (Hall & Jones 2010), the western United States for 1971-2000 (Jones et al. 2010), and selected New Zealand wine regions from Tables 2 and 3. Climate indices are 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) ; table is sorted by GST.

Country/State	Region	Area[1] (km^2)	Elevation (m)	GST (°C)	GDD	HI	BEDD
New Zealand	Otago	1089	340	13.8	805	1402	841
Germany	Mosel Valley	198	179	14.0	891	1411	966
Germany	Rheinhessen (Rhine Valley)	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
New Zealand	Wairau Valley (Marlborough)	611	80	15.1	1068	1533	1094
France	Burgundy	260	264	15.2	1118	1648	1171
New Zealand	Nelson	308	34	15.2	1101	1508	1122
New Zealand	Bay of Plenty	1821	184	15.8	1220	1550	1203
Italy	Valtellina Superiore	5	476	16.2	1335	1880	1304
New Zealand	Hawkes Bay	599	29	16.3	1334	1732	1358
France	Bordeaux	1471	50	16.5	1387	1890	1382
New Zealand	Gisborne	228	21	16.6	1390	1761	1411
Spain	Rioja	605	506	16.6	1410	1886	1343
Australia	Yarra Valley	3120	251	16.6	1343	1810	1179
New Zealand	Kumeu	52	36	16.6	1401	1688	1386
Washington & Oregon	Walla Walla	1306	317	17.1	1528	2296	1480
France	Côtes du Rhône Méridionales	1440	174	17.3	1570	2067	1447
Australia	Coonawarra	400	65	17.4	1511	2046	1330
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
New Zealand	Bay of Islands	465	52	17.6	1606	1827	1521
Italy	Chianti Classico	101	321	17.9	1685	2112	1507
Portugal	Porto	807	437	17.9	1684	2155	1489
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
Australia	Barossa Valley	590	278	19.0	1852	2342	1489
Australia	Margaret River	2640	75	19.2	1887	2092	1584
California	Lodi	2195	24	20.3	2211	2797	1980
Spain	Jerez-Xéres-Sherry	126	57	20.9	2343	2441	1921

[1] Area is rounded to the nearest 1 km^2 (100 hectares) and is approximate due to the resolution and precision of the wine region boundary data.

(Figure 4). Median wine region values for GST and GDD are functionally the same with a correlation coefficient close to unity (*r* > 0.9998) while the lowest values are seen with HI and the other indices. An examination of the within region structure of GDD shows the spatial suitability characteristics of each wine region (Figure 5). The Bay of Islands region is 94 % WI Region II but has a small area of WI Region III (6 %). The Bay of Plenty straddles three WI Regions with the majority (51 %) in WI Region Ib (Figure 5). While the Gisborne wine region is nearly evenly split between WI Region Ib (49 %) and II (51 %), Hawkes Bay is predominately WI Region Ib (95 %). Kumeu, a relatively small region on the North Island was classed as WI Region Ib (23 %) and II (77 %). Wairau Valley and Nelson, although different in size, share similar spatial GDD distributions with 63-64 % WI Region Ia and 32-37 % WI Region Ib, respectively (Figure 5). Finally, the Otago region has only 35 % of its area in WI Region Ia, while 65 % was considered potentially too cool on the WI.

The value of doing spatial quantile statistics within viticulture regions can be seen by examining the entire suite of statistical parameters. For example, smaller regions with low elevation differences (e.g., Henderson, Kaitaia, and Matakana) typically exhibit very low ranges from the minimum to maximum grid values for each index (Table 3). In these cases, the region has similar winegrape climate suitability over the whole area. As expected, larger regions and those with greater elevation ranges, on the other hand, tend to have broader suitability differences. For example, the Bay of Plenty region is the second largest area, has the second greatest elevation range, and therefore exhibits a wide range of maturity suitability (in terms of GST, from cool to warm). Furthermore, the three regions that are consistently either very near or below the lower thresholds in each of the four indices (South Canterbury, Otago, and Christchurch) show that the estimated wine region areas encompass elevations that are too high and therefore too cold for viticulture (Table 3). Within these regions, a better representation of their climate suitability would be to use the median to maximum range or the 75th percentile to maximum range. Doing so would find that there are zones within each region that have cool to possibly even intermediate climate suitability for winegrape production.

DISCUSSION

In this research, the use of spatial climate data for

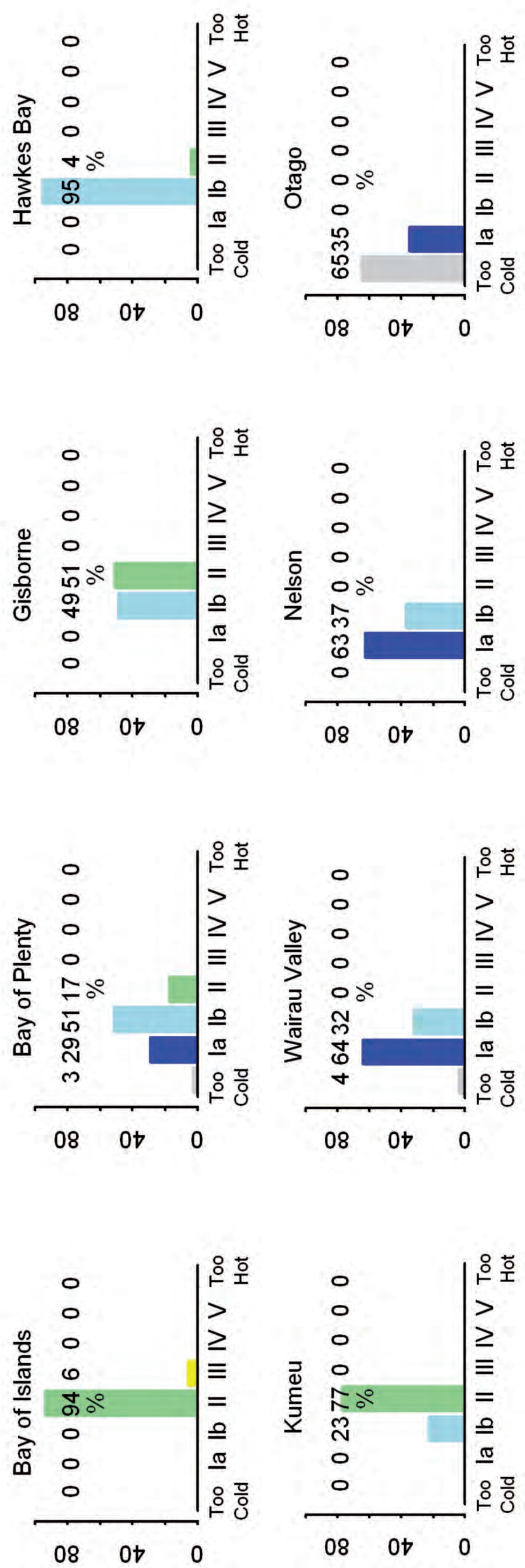

Figure 5 - Distribution of Winkler Region climate types (growing degree-days) within eight of the New Zealand wine regions ranging from north to south and cool to warm growing conditions as given in Table 1.

New Zealand has produced a depiction of the characteristics and structure of wine region climate indices commonly used in viticulture suitability studies (Jones *et al.*, 2010). As expected, the overall results depict a climatically cool to moderately warm country for viticulture and wine production. For New Zealand, viticulture-climate suitability is strongly tied to latitudinal location and extent, along with elevation, resulting in a relatively wide range of climates that can be found along both the North and South Islands. The continentality found in other wine regions (e.g., Europe, Australia, and the United States) is less pronounced in New Zealand due its maritime location (away from continental land masses) and relatively narrow geography (there is no land in New Zealand that is more than 150 km from a coast).

The comparison of four commonly used climate indices in viticulture provides insights into their usefulness in New Zealand. It is apparent from Figures 2 and 3 that each index largely depicts the known climate structure for the country ; however, subtle differences are also evident. While the indices were found to be highly spatially correlated, GST tends to better characterize interregional differences but is poor at capturing the intraregional differences when compared to the other indices (Figure 2). For growing degree-days, even using the updated lower limits for GDD (Winkler Index) found by Jones *et al.* (2010), many of the South Island regions are limited to too cool or Region Ia or Ib categories. The GDD results found in this research generally agree with values given by Jackson and Schuster (2001) for some regions in New Zealand. These authors showed that station values in the Otago region ranged from 850-1000 GDD, while this research shows the median to maximum grid values in the region are 805-1022 GDD (Table 3). For the Northland area (northern North Island), Jackson and Schuster (2001) estimated a range of 1300-1400 GDD for wine producing areas, while this research finds that areas such as Kaitaia, the Bay of Islands, Whangarei and Matakana range from 1268-1694 GDD (Table 3). The HI, owing to additional weighting to maximum temperatures, tends to better capture the broad and within region structure of climate suitability in the country (Figure 3). However, the HI tends to be lower in New Zealand than other regions in the western US, Australia, and Europe having similar GST, which is likely due to shorter day lengths due to the lower latitudes in New Zealand. The BEDD on the other hand, captures the spatial variations in the North Island better than the cooler conditions over the South Island (Figure 3). This is likely due to the additional diurnal temperature range (DTR) adjustment in the BEDD, which may not be appropriate for the latitudes and/or the generally cooler nights experienced in New Zealand.

Comparison of the median viticulture-climate index values found in this research with those of the western US (Jones *et al.*, 2010) and Australia (Hall and Jones, 2010) reveals a generally similar correlation structure. First, GST and GDD for all three areas are functionally the same with correlations close to one (Figure 4 this study, others not shown). Second, similar correlations and slightly more curvilinear relationships were found between the other three indices and are due to the differences in the way maximum temperatures are weighted in the HI and the upper threshold and additional DTR adjustment used in the BEDD (Gladstones, 1992). The near perfect relationship between GST and GDD found in this study and others (Jones *et al.*, 2010 ; Hall and Jones, 2010) is very useful as the calculation of GST overcomes the majority of the fundamental issues with GDD (McIntyre *et al.*, 1987 ; McMaster and Wilhelm, 1997 ; Jones *et al.*, 2010). Namely, GST is much easier for all users to understand, requires a simple averaging procedure, and does not use a base or upper temperature threshold as in GDD (neither of which are exactly specified for all cultivars and all regions) (Moncur *et al.*, 1989 ; Roltsch *et al.* 1999).

Furthermore, similar research for the western United States for 1971-2000 (Jones *et al.*, 2010), Australia for 1971-2000 (Hall and Jones, 2010), and Europe for 1950-2000 (Jones *et al.*, 2009) has enabled an examination of commonly compared wine regions (Table 4). Viticulture region median climate values place the majority of the wine regions examined in this study generally toward the cooler regions depicted in Table 4. For example, Otago compares climatically to the Mosel and Rhine valleys of Germany and the Champagne region of France, although the higher elevations in Otago make it slightly cooler overall and potentially one of the coolest commercial wine growing regions in the world. Wairau Valley and Nelson are both climatically similar to the Willamette Valley of Oregon and Burgundy, France, while Hawkes Bay and Gisborne are more similar to Bordeaux, Rioja, and the Yarra Valley of Australia (Table 4). The Bay of Islands, one of the warmest New Zealand regions, compares climatically to numerous areas in Italy and Portugal. Differences in wine region sizes and elevations in Table 4 are evident, with the larger areas and those with greater elevation ranges having greater within-region spatial variability on all climate indices (not shown). Furthermore, because New Zealand's cool nights throughout the growing season typically produce fruit that is nearly always higher in acidity (Jackson and Schuster, 2001), comparisons with European locations should also consider the lower DTRs that result from higher humidity levels during the growing season (Jones *et al.*, 2009).

While the viticulture regions used in this research were estimated based upon published data on vineyard locations (Tait, 2005), preliminary boundaries created by some of the regions, recent aerial imagery, and digital elevation data, the results are likely to be reasonably valid in the future when New Zealand further develops legal national GIs. The methods used to produce these boundaries are not likely to be dramatically different, or different enough from the development of national GI regions to produce a wide difference in the spatial assessment of climates in New Zealand. The most likely differences will be in the cool climate regions, such as Otago, where more exact region boundaries would arguably better define the cool climate limits due to elevation in the region. Further differences will likely occur with changes in the overall area in viticulture regions, whereby decreases or increases in size will alter the number of grid squares in graphical representations and therefore the climate summaries for those regions. Furthermore, some differences are bound to occur between the designations and use of GI zones, regions, and sub-region boundaries. However, it would be prudent to redo this analysis once legally accepted GIs have been created for New Zealand.

In addition to the potential differences in the spatial climates due to viticulture region boundary changes, this research should be redone in the future to take into account changes in climate, which are occurring more rapidly today than in the past (IPCC, 2007). Temperatures in wine regions worldwide have increased 1-3 °C over the last 25 to 50 years (Jones *et al.*, 2005; Hall and Jones, 2009) and approximately 0.1 °C/decade in New Zealand (Mullan *et al.,* 2010), which would mean that the 1971-2000 climate normals used in this research should be updated to the next period normals once the data become available. For example, Jones *et al.* (2010) showed that GDD values from stations from the 1971-2000 climate normals in the western US were on average 10 % higher than those experienced during the middle of the 20th century. Furthermore, using 1974-2003 gridded climate data and downscaled climate model output, Tait (2008) has projected significant changes in GDD and frost occurrence in New Zealand. Comparing two future periods to today, the research showed an increase in the area of the country with GDD greater than 1000 from 38.2 % to 50.7 % by 2020-2049 and 65.3 % by 2070-2099. In addition, the research showed that the area of the country that currently experiences fewer than six frosts in the spring will increase from 54.5 % to 62.7 % and to 77.1 % over the same time periods, and that 23.1 % of the country will likely be frost free in spring by 2070-2099 (Tait, 2008). Taken together, changes of these magnitudes show that the proportion of New Zealand's land area potentially suited to growing winegrapes may significantly increase over the coming century. These changes will have different influences/impacts for different regions. Already suitable areas might warm beyond what is considered suitable for the cultivars currently grown there (Jones *et al.*, 2005), while marginal areas (where GDD and/or frost risk are at, below or higher than what is considered economically viable) will possibly become better suited to viticulture and wine production in the future (Tait, 2008). However, it is important to note that the Tait (2008) study did not examine potential changes in rainfall and humidity on grape growing suitability or the possible impacts of new diseases, pests or weeds that might coincide with the projected changes in temperature.

CONCLUSIONS

Understanding viticulture region spatial climate characteristics provides researchers, growers, and wine producers information with which to assess a region's suitability for viticulture. However, climate information for viticulture regions is often limited to one or maybe a few stations, which are often not located in close proximity to vineyards and commonly with limited or inconsistent time periods. The use of spatially interpolated climate normal data overcomes these issues by providing the means by which the entire landscape in a given wine producing region can be assessed for its climate structure and suitability for any crop.

Results from this research show that each of the four climate indices depicted a broad structure across a range of mostly cool to moderately warm climates suitable for viticulture in New Zealand wine producing regions. A comparison of the GST and GDD indices reveals that they functionally capture the same information with little difference other than magnitude. While the use of GDD has historically been very common in assessing viticultural suitability or helping to determine 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 index appears to capture the expected structure of the New Zealand viticulture regions, benefiting from the higher weighting of daytime maximum temperatures and the application of a latitudinal adjustment that helps to account for increasing day lengths at the latitudes of New Zealand. The BEDD index also provides good regional depiction of known climate suitability ; however, it performs better over the warmer North Island than it does over the cooler South Island due to higher diurnal temperature ranges in New Zealand than in Australia, where the index was developed. However, to determine which index is better for use in New Zealand will require additional within-region assessment that is beyond the scope of this study.

This research has shown that developments in spatial climate data products have enhanced the depiction and assessment of climate characteristics in wine producing regions by accounting for climate variations over the entire landscape. However, we acknowledge that this type of data is synthetic, has errors associated with localized atmospheric dynamics (e.g., inversions, land-sea breezes, etc.), and depends on the observational data available, the density of which varies from region to region (Tait, 2008). It is also important to note that micro-scale site differences are still not fully depicted in our spatial climate data, but the ~500 m resolution of the NIWA climate grids provides a substantial improvement in understanding general regional climate characteristics over the use of a single or a few stations. Furthermore, the application of producing a statistical range of climate over entire wine producing regions allows for a more complete assessment of the spatial climate characteristics within them.

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, given that New Zealand wine producing regions will likely become more formalized than those used in this study (legal GI designations) and that climates are changing rapidly, this work should be updated so that wine region climate suitability can be monitored and reported appropriately and in a timely manner.

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