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Article abstract

New Zealand produces premium quality wines and its wine industry is growing rapidly. The winegrowing regions have growing degree-days that range from 900 in cool Central Otago and Canterbury, to more than 1600 in the warmest region in the country, Auckland. Average growing season temperatures for the same regions range from approximately 14.3°C to 17.6°C. Most trophy-winning red wines are grown in areas with a climate cooler than where similar wines are grown to high standard internationally. New Zealand vineyards are planted mainly on flat alluvium and aggradation gravels with slopes of less than 3°. Rapid growth is pushing new plantings onto adjacent hillsides that are underlain by greywacke, schist, and (less commonly) limestone. The expansion of the industry onto these different substrates will affect grape and wine characteristics and may lead to new styles of New Zealand ultra-premium wines.

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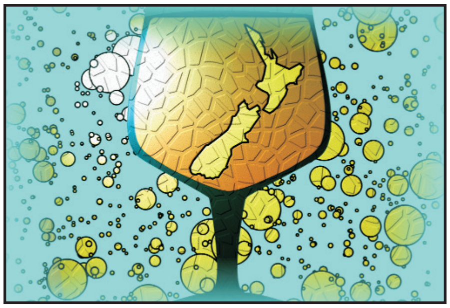

Geology and Wine 12. New Zealand Terroir

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SUMMARY
New Zealand produces premium quality wines and its wine industry is growing rapidly. The winegrowing regions have growing degree-days that range from 900 in cool Central Otago and Canterbury, to more than 1600 in the warmest region in the country, Auckland. Average growing season temperatures for the same regions range from approximately 14.3°C to 17.6°C. Most trophy-winning red wines are grown in areas with a climate cooler than where similar wines are grown to high standard internationally. New Zealand vineyards are planted mainly on flat alluvium and aggradation gravels with slopes of less than 3°. Rapid growth is pushing new plantings onto adjacent hillsides that are underlain by greywacke, schist, and (less commonly) limestone. The expansion of the industry onto these different substrates will affect grape and wine characteristics and may lead to new styles of New Zealand ultra-premium wines.

SOMMAIRE
La Nouvelle-Zélande produit des vins de hautes qualités et son industrie vinicole croît rapidement. Les degrés-jours de croissance des régions vinicoles vont de 900 dans les régions fraîches d'Otago et de Canterbury, et dépasse 1 600 dans la région d'Auckland, la plus chaude du pays. Les températures de croissance moyenne pour ces mêmes régions vont de 14,3 °C à 17,6 °C. La plupart des vins rouges primés proviennent de régions au climat plus frais que leurs équivalents ailleurs dans le monde. Les vignes de Nouvelle-Zélande sont cultivées dans des sols alluvionnaires plats et des graviers d'aggradation au pendage de moins de 3°. La croissance rapide de l'industrie vinicole entraîne la plantation de vignes sur les sols des collines environnantes qui recouvrent des formations de grauwackes, de schistes argileux, et plus rarement de calcaires. L'expansion de l'industrie vinicole sur ces nouveaux substrats aura des répercussions sur les caractéristiques du raisin et du vin, ce qui pourrait donner de nouveaux styles de très grands vins de Nouvelle-Zélande.

INTRODUCTION
The New Zealand wine industry has experienced significant growth in the last ten years and produces some ultra-premium wines. From 1996 – 2004, New Zealand wines commanded the highest price per litre on the UK market (New Zealand Trade and Enterprise (NZTE) 2007). The vineyards that produce these premium wines are located in regions ranging from cool with ~900 growing degree days (GDDs) and an average growing season temperature of 14.3°C, to warm with more than 1600 GDDs and an average growing season temperature of 17.6°C; each of these areas produce wines having unique profiles. Plantings throughout New Zealand are on a variety of soil types, and little work has been done to examine how soils and geology affect wine quality in a New Zealand context. However, geology and soils affect grape characteristics in other countries, although it is often difficult to link specific subsurface properties to quantified changes in grape properties (e.g. Wilson 1998; Macqueen and Meinert 2006). Variations in geology correlate with variations in the Appellation d'Origine Contrôlée (AOC) labelling system in France, suggesting that geology has a role in determining grape properties (Wilson 1998).

The use of geographic information systems (GIS) for precision viticulture and spatial analysis of wine-growing regions is providing increasing benefits to the industry. For example, Carey et al. (2003) show how data integrated into a GIS can be used to delineate zones of viticultural potential on both a micro and macro scale in South Africa, whereas Jones et al. (2004) show that GIS can be used to analyze the terroir potential of the Umpqua Valley in Oregon. Aerial imagery combined with GIS has also been used for various other tasks, including the analysis and management of phylloxera (an insect pest of commercial grapevines; Johnson et al. 1996), delineation of areas of differing vigour (e.g. Johnson et al. 2001a, b, 2003; Nemani et al. 2001), analysis of soil loss in modernized, improperly managed vineyards (Martínez-Casasnovas and Sánchez-Bosch 2000), profitable implementation of precision viticulture (e.g. Bramley et al. 2003), and the assessment of viticultural performance (Bowen et al. 2005). We used GIS as a tool to georeference vineyard locations and to analyze the geology and climate of vineyards in New Zealand; these analyses can be used to determine areas of potential viticulture in desired regions where land is becoming increasingly scarce. Such analyses can also be performed in the future using similar datasets in order to observe the development of the industry over time and to track industry trends.

This paper presents the first national survey of the geological setting of New Zealand vineyards, and we speculate on how these vineyards might expand onto diverse soil types that reflect underlying geology. We also provide an overview of climate, slope, aspect, and the varietals planted in New Zealand vineyards as a whole and for individual regions. Taken together, the results help define the terroir of the New Zealand wine industry in 2007. As the industry continues to expand, it will be possible to do similar analyses in the future, and to compare these analyses with the baseline data presented herein so that a clear understanding of how the New Zealand wine industry develops over time can be obtained.

GEOLOGY OF NEW ZEALAND

New Zealand is a young and dynamic continent; it sits on the boundary between the Australian Plate and the Pacific Plate. New Zealand is the emergent landmass of the continent of Zealandia, and the plate boundary cuts through the South Island as the Alpine Fault, which has a right-lateral strike-slip offset of 480 km (Graham 2008). The oldest rocks in New Zealand are Cambrian, but these and other Paleozoic rocks are not widespread, and they occur only along the western margin of the South Island (Fig. 1). Most of the basement in New Zealand is Mesozoic greywacke, which is widespread in both the North and South islands, and occurs as schistose metagreywacke (Haast Schist) in large parts of the South Island (Fig. 1). New Zealand also has an unusually thick and complete section of Cenozoic rocks, most of which are marine sedimentary rocks, including limestone, siltstone, and sandstone. Large areas in the North and South islands are covered by Quaternary glacial and fluvial sediments, and Quaternary volcanic rocks are widespread in the North Island (Fig. 1). Outwash deposits are widespread in the lowlands of the North and South islands; we refer to these herein as aggradation gravels.

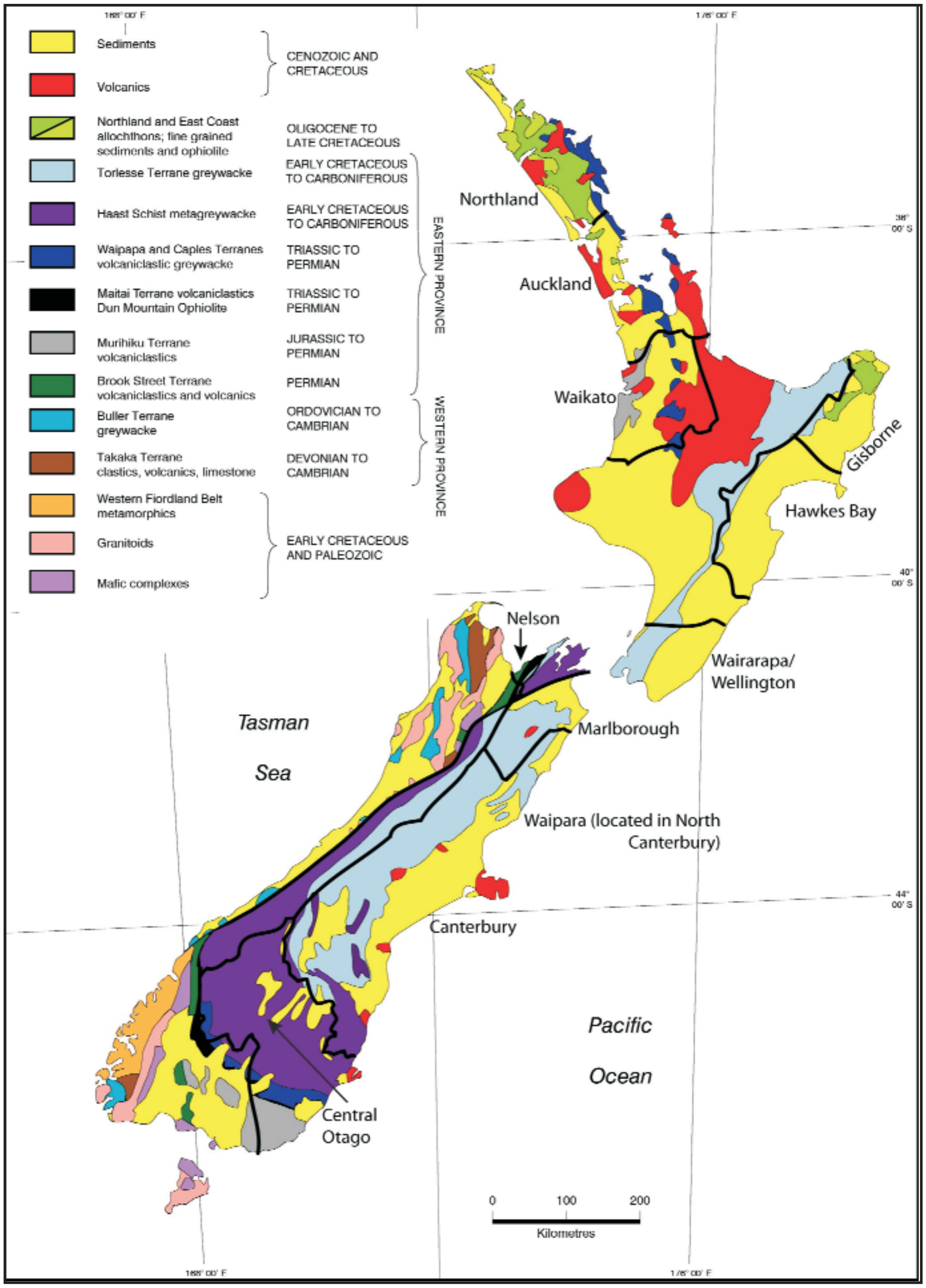

Figure 1. Map of New Zealand geology showing locations and boundaries of major winegrowing regions (geological data of New Zealand was sourced from GNS Science).

DATA AND METHODS

Frontier Global Limited conducted the 2006 Vineyard Survey for New Zealand Winegrowers. Vineyard locations are continually being georeferenced and integrated into a GIS, which allows for spatial analysis of plantings. This analysis was performed on the vineyard database in early 2007. For the georeferenced vineyards used in this analysis, parcel centroids were created for the aspect and slope calculations (centroid coordinates typically provide the best method to represent the location of a parcel). Legal land parcels were used, although the data analysis cannot determine where the vineyard is actually planted inside the legal land parcel. Different types of geology within a planted legal land parcel, for example, will be included in the calculations regardless of where the vines are actually planted within that parcel. In some cases one vineyard may overlap several different legal land parcels; each land parcel is treated as a separate entity in these analyses even though all parcels may be managed as one contiguous block.

The geological data for New Zealand were sourced from the Institute of Geological and Nuclear Sciences, or GNS Science (copyright reserved). The 2004 update of the 1:1 000 000 data series was used because that dataset is complete on a national scale. The aspect data were calculated using the Spatial Analyst Aspect function in ArcMap 9.1. The digital elevation model (DEM) used for this calculation is based on 40 m cell sizes created from Land Information New Zealand (LINZ) 20 m contours and spot heights by GNS.

Landcare Research Manaaki Whenua created an environmental classification of the whole of New Zealand (http://www.landcareresearch.co.nz/services/service_details.asp?Service_Tool_ID=29). The Land Environments of New Zealand, or LENZ, classification is based on a set of 15 underlying climate, landform and soil variables. For an examination on a national to regional level, a map scale of 1:1 000 000 (LENZ level II classification) is recommended, which is also consistent with the QMAP (New Zealand's digital geological mapping project) scale used in this analysis (Leathwick et al. 2002). The LENZ slope layer was used to calculate the slope of vineyards. The slope layer was created by Landcare Research using in-house software, and was based on a 25 m digital elevation model fitted to 20 m digital contour data from New Zealand map series 260 (Leathwick et al. 2002).

Climate data were sourced from the National Institute of Water and Atmospheric research (NIWA). Data from selected climate stations located in close proximity to vineyards in the studied regions were used. Because of data limitations, it was not always possible to select the ideal station and these data should be used to indicate general trends only. All data on varieties planted and tonnage harvested were sourced from New Zealand Winegrowers, and based on data collected in 2006.

As a proxy for quality, we compiled a list of trophy-winning wines from four New Zealand wine competitions: the Bragato Wine Awards (2005-2007), the Royal Easter Show (2006-2007), the New Zealand International Wine Show (2005-2006) and the Air New Zealand Wine Awards (2005-2007). Trophies awarded to single varietal wines, and to rosé wines and red blends from the same region, were used in the analysis. Wines winning multiple trophies at one event were counted only once, and wines winning awards unrelated to variety, such as Champion Export Wine and Champion Amateur Wine, were not counted in the analysis (note: a complete list of the trophy-winning wines used in these analyses can be found at http://www.wineshow.co.nz). Numbers of award winning wines are also compared to the total area planted in each region to calculate a trophy-to-planted-area ratio.

Table 1. Areal extent of New Zealand vineyards and percentage of grafted versus ungrafted plantings (NZWG 2006).

Region	Area (ha)	Percentage of total NZ vineyard area	Grafted Ha (% of Region)	Ungrafted Ha (% of Region)
Auckland	489	2.2%	482 (98%)	7 (2%)
Canterbury	272	1.2%	53 (20%)	219 (80%)
Central Otago	1251	5.7%	713 (57%)	538 (43%)
Gisborne	1911	8.7%	1827 (96%)	85 (4%)
Hawkes Bay	4341	19.7%	4031 (93%)	310 (7%)
Marlborough	11,476	52.0%	11,255 (98%)	221 (2%)
Nelson	695	3.2%	502 (72%)	193 (28%)
Northland	14	0.1%	14 (100%)	0 (0%)
Other	23	0.1%	22 (96%)	1 (4%)
Waikato/ Bay of Plenty	150	0.7%	139 (93%)	11 (7%)
Waipara	652	3.0%	460 (71%)	192 (29%)
Wairarapa	776	3.5%	587 (76%)	189 (24%)
All of New Zealand	22,051	-	20,085 (91%)	1966 (9%)

RESULTS

New Zealand has eleven viticultural regions and more than 22 000 ha of vineyards (Fig. 1; Table 1). Marlborough is the largest viticultural region, accounting for more than 50% of total vineyard area, or slightly less than 11 500 ha. Hawkes Bay and Gisborne are the next largest regions, occupying less than 20% and 9%, respectively. These three regions account for more than 80% of all viticultural land in production in New Zealand. This section provides an overview of the geology, slope, aspect, varietals planted and climate data for New Zealand as a whole and for the individual regions listed in Table 1.

On a national scale, Sauvignon Blanc accounts for roughly 40% of land under vine (Fig. 2a), yet accounts for more than 50% of harvested tonnage (Fig. 2b). The difference can be attributed to high yields compared to other cultivars such as Pinot Noir, which occupies 18% of total acreage and accounts for only 12% of tonnage harvested. Chardonnay is the third major variety, occupying 17% of total land and 15% of harvested tonnage. As each region is discussed in greater detail below, more information on cultivars is provided.

Some regions in New Zealand have large areas of ungrafted vines, which are especially vulnerable to phylloxera (Table 1). With the spread of phylloxera into previously unaffected areas, this has the potential to be costly in some regions. Central Otago is particularly at risk, as 43% (538 ha) of

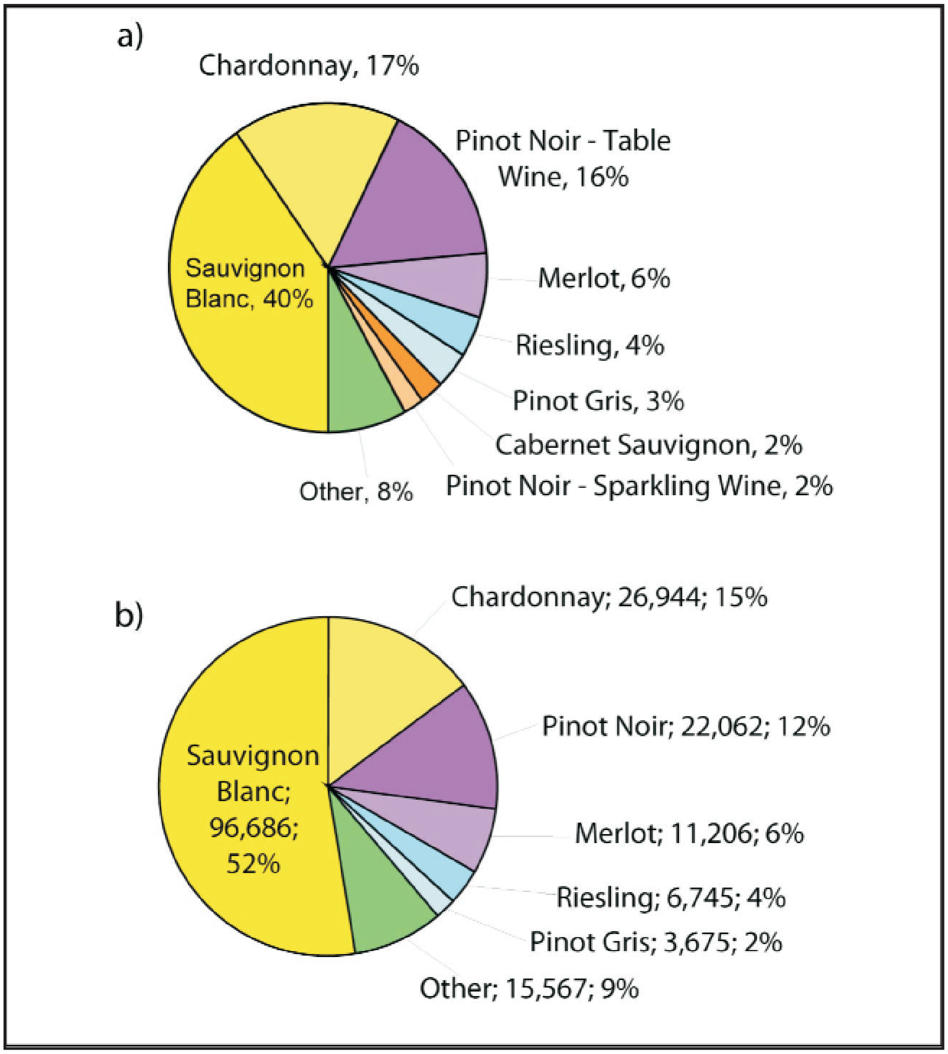

Figure 2. New Zealand wine industry data showing a) plantings by variety as a percentage of total plantings, and b) 2006 tonnage by variety harvested as a percentage of total tonnage (NZWG 2006).

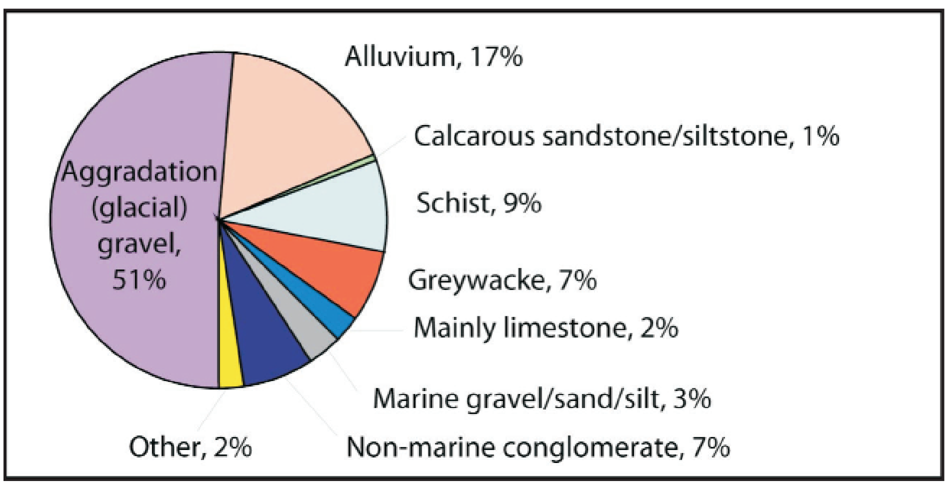

Figure 3. Main geological units that underlie New Zealand vineyards, expressed as percentage of total vineyard area (geological data of New Zealand was sourced from GNS Science; this study).

land under vine is planted with ungrafted vines. Because depth and texture of soil may influence the spread of phylloxera (Wildman 1986; Chitkowski and Fisher 2005), it is important to document where these vines are located and how the spread of phylloxera may be influenced by subsurface characteristics.

Most New Zealand vineyards (68%) are located, in general, on alluvium and aggradation gravels (Fig. 3). In the Marlborough and Waipara regions, the proportion of vineyards situated on these substrates is 75% and 90%, respectively. Another major geological unit on a national scale is schist, which underlies roughly 9% of national plantings and approximately 50% of all plantings in Otago region. Approximately 7% of national plantings are on greywacke; more than 10% of plantings in Marlborough and 7% of plantings in the Auckland/Northland region are underlain by greywacke.

Plantings in New Zealand are generally located on very flat land. Approximately 66% are located on land with a slope of <1° (Fig. 4). Plantings on steeper land with a slope of greater than 5° account for only 7% of overall land under vine in the country. Approximately 40% of vineyards are planted on sites that are flat and therefore have no aspect, whereas 34% face northeast, north or northwest, consistent with the northern aspect that is expected in the southern hemisphere (Fig. 5).

In the New Zealand wine-growing regions, temperatures range from cool in the southern areas of Canterbury and Central Otago to intermediate-warm in other regions of the country (Fig. 1; Table 2). Solar radiation is also lowest in the southernmost regions, where more vineyards are planted on steeper slopes. Annual water deficits vary from low in areas such as Auckland, where irrigation is usually not required, to very high in Central Otago, where irrigation is more common, at least in newly established sites. Most areas are classified as cool to intermediate, and based on GDDs, fall within Amerine and Winkler regions I and II (Amerine and Winkler 1944). The Latitude Temperature Index (LTI) was developed at Lincoln University in New Zealand and is use-

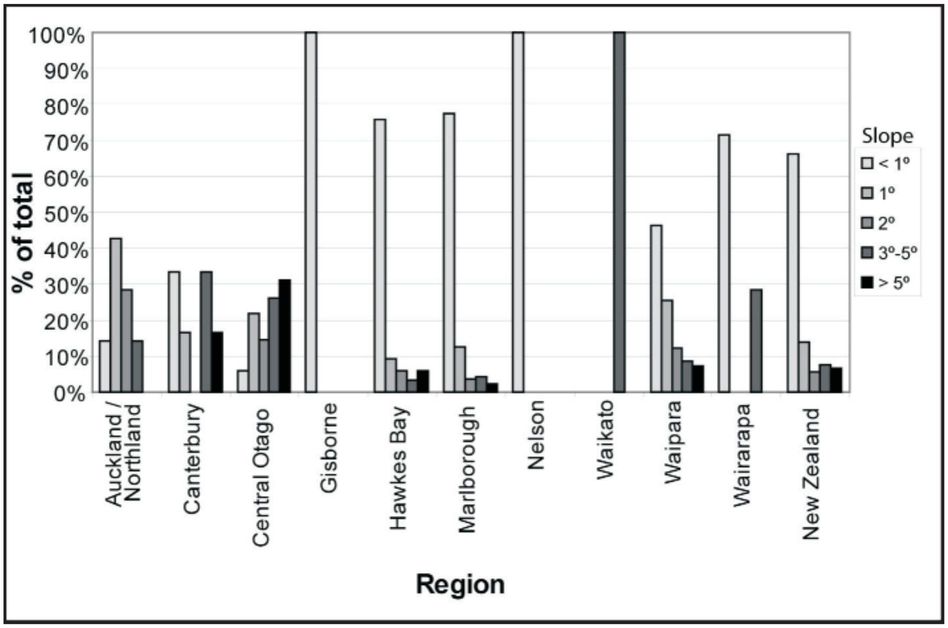

Figure 4. Distribution of vineyard slopes in the major winegrowing regions of New Zealand (Leathwick et al. 2002; this study).

ful in comparing climates in cooler regions (Jackson 2001). The LTI was calculated for each region as:

LTI = (mean temperature of the warmest month) * (60 -°latitude)

LTI values below 380 are classified as the cooler Region I and are subdivided into IA (LTI <190), IB (LTI 190-270) and IC (LTI 270-380). Wairarapa, Nelson, Marlborough and Waipara are the warmer districts in Region I, having LTI values of IC. Canterbury and Central Otago are the coolest regions, with LTI values of IB – IC, and most areas examined in Central Otago are characterized by cooler LTI values of IB.

Jones (2006) examined the relationships between phenological requirements and climate for selected major world winegrowing regions that produce premium and high quality wines (Fig. 6a). These data are compared with average growing season temperatures (+/- one standard deviation) for selected climate stations in major New Zealand winegrowing regions (Fig. 6a). Many of the trophy-winning wines in selected New Zealand wine competitions are grown in regions featuring similar climatic patterns (Fig. 6b), although some of the major red varieties grow in regions cooler than typically found elsewhere. For comparative purposes we present growing degree-days for each New Zealand winegrowing region (Fig. 7).

Although Nelson has only 3.2% of the total vineyard area in New Zealand, 7% of the trophy wines are grown here, giving it the country's highest trophy-to-planted-area ratio (Table 3). Nelson has the lowest standard deviation of average growing season temperature, indicating that it has a relatively stable climate, which may lead to more consistent vintages. Hawkes Bay has the second best trophy-to-planted-area ratio and has the second lowest standard deviation of average growing season temperature. The relatively stable climates are likely to be at least partly responsible for the success of wines produced in these regions and their more consistent vintages. Marlborough, with more than 50% of vineyard area and 39% of awarded trophies, is ranked sixth. It is important to note that these percentages do not reflect the actual number of entries, and many premium wines are not entered into such competitions. Areas such as Marlborough that specialize in one type of wine might also be at a disadvantage in this type of analysis because there is only one trophy awarded for each varietal. Regions that have more varietals planted, such as Nelson and Hawkes Bay, may have a slight advantage in such analyses because they are eligible for more trophies. Therefore, these analyses should be used as general guides only.

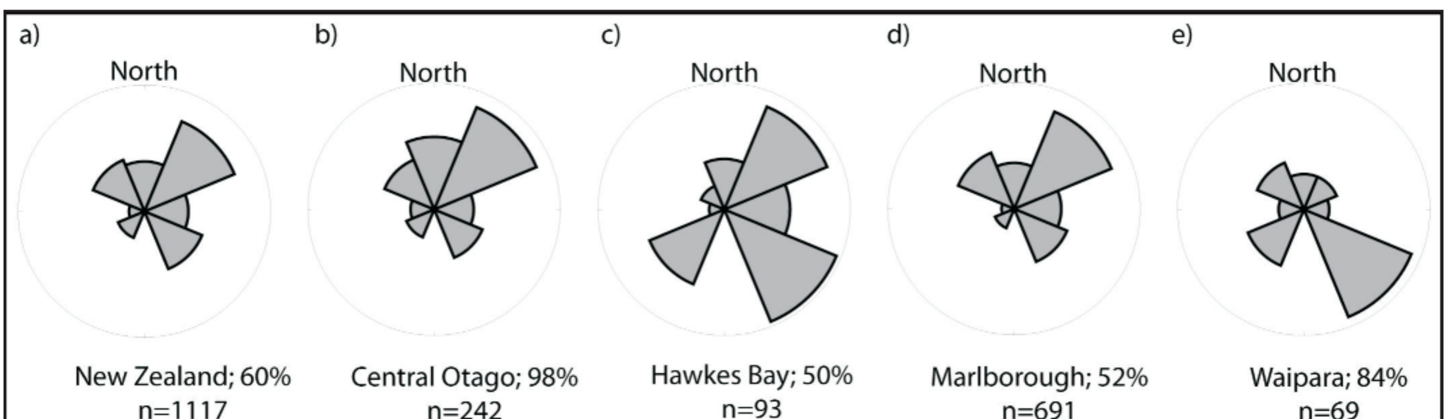

Figure 5. Aspects of vineyards in New Zealand (a) and in selected regions (b-e). The percentage value refers to the percentage of vineyards that have an aspect value, and are therefore represented in the figure. The remaining vineyards are flat and have no aspect value (Leathwick et al. 2002; this study).

Table 2. Selected climate and landform characteristics of the major winegrowing regions in New Zealand. (Leathwick et al. 2002; NIWA National Climate Database: http://cliflo.niwa.co.nz/; this study).

Region	Mean annual temp (°C)	Mean minimum temp of coldest month (°C)	Mean annual solar radiation (MJ/m2/day)	Mean winter solar radiation (MJ/m2/day)	October vapour pressure deficit (KPa)	Monthly water balance ratio	Mean annual water deficit (mm)	Approximately GDD using monthly temperatures of growing season	LTI Region	Average T during growing season (°C)	Landform
Auckland	14.2 - 14.7	5.1 - 6.3	14.9 - 15.0	5.9 - 6.2	0.4	2.6 - 2.7	40.3 - 43.5	1617	II	17.6	very gently undulating hills
Northland	14.2 - 14.7	5.1 - 6.3	14.9 - 15.0	5.9 - 6.2	0.4	2.6 - 2.7	40.3 - 43.5	1510	II	17.1	very gently undulating hills
Canterbury	9.5 - 10.5	-0.9	13.0 - 13.6	4.0 - 4.3	0.4	1.6 - 1.9	82.4 - 112	927	IB - IC	14.4	undulating plains
Central Otago	8.1 - 10.2	-2.2	13.0 - 13.9	3.6 - 4	0.4 - 0.5	1.0 - 2.4	51.3 - 307	908	IB - IC	14.3	rolling lower hillslope and basin floors as well as gently undulating flood plains and some steep slopes
Gisborne	13.3 - 13.6	3.1 - 3.3	14.6 - 14.7	5.4	0.5	1.7 - 1.8	169 - 183	1394	II	16.7	flat flood plains to gently undulating plains
Hawkes Bay (Hastings)	12.3 - 13.6	2.5 - 3.8	14.6 - 14.8	5.0 - 5.8	0.4 - 0.5	1.7 - 2.9	34.0 - 183	1415	II	16.7	flat flood plains and undulating hills
Marlborough (Blenheim)	11.2 - 12.7	0.6 - 3.1	14.1 - 15.3	4.4 - 5.4	0.5 - 0.6	1.4 - 2.4	110 - 261	1165	IC	15.5	flat flood plains to undulating plains
Nelson	12.3	2.5	14.7	5.0	0.4	2.4	90.6	1112	IC	15.3	undulating plains
Waikato / Bay of Plenty	12.1 - 14.2	2.6 - 5.1	14.8 - 14.9	5.7 - 5.9	0.3 - 0.4	2.6 - 3.7	5.2 - 43.5	1068	II	16.1	very gently undulating hills to undulating hills
Waipara	11.3	0.6	14.0 - 14.1	4.4	0.5	1.7 - 1.8	182 - 183	1038	IC	14.9	flat plains to very gently undulating plains
Wairarapa (Masterton)	12.7	3.6 - 3.7	14.2	4.7	0.4	2.3 - 22	107 - 965	1033	IC	14.9	flat plains to flat flood plains

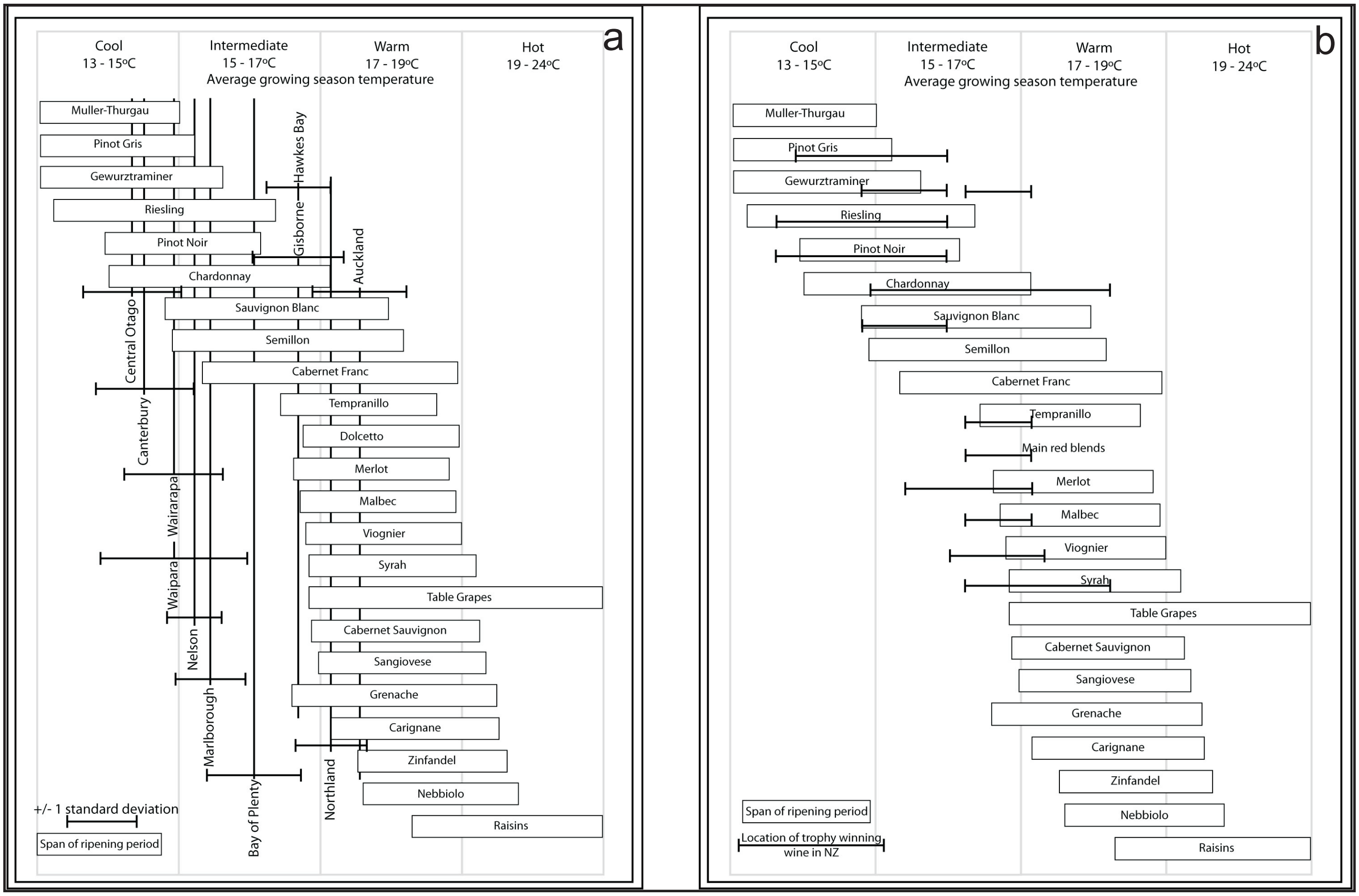

Figure 6. a) Ripening period of selected varietals in major winegrowing areas of the world (Jones 2006) versus average growing season temperatures of main winegrowing regions in New Zealand (NIWA National Climate Database: http://cliflo.niwa.co.nz/; this study). b) Ripening period of selected varietals in major winegrowing areas of the world (Jones 2006) versus the location where trophy winning wines from the Bragato (2005-2007), Royal Easter Show (2006-2007), New Zealand International Wine Show (2006-2007) and Air New Zealand (2005-2007) wine awards were grown in New Zealand [http://www.wineshow.co.nz].

WINEGROWING REGIONS OF NEW ZEALAND

This section presents descriptions of the major winegrowing regions in New Zealand. For each region, a summary of vineyard plantings and selected environmental characteristics is provided. The discussion section then examines how these environmental conditions may affect the grape characteristics of selected varieties in New Zealand now and in the future.

Auckland / Northland

Plantings in Auckland are a mix of red and white varieties totalling 489 ha (Table 1; Fig. 8a). Northland plantings total 14 ha and are mainly white varietals (Table 1; Fig. 8b). Auckland and Northland, with more than 1600 and 1500 GDDs and average growing season temperatures of 17.6°C and 17.1°C, respectively, are the two warmest regions in New Zealand (Fig. 7; Table 2). However, these climate conditions vary depending on which climate gauges are used, and some areas in Northland have more GDDs than some areas in Auckland and vice versa. The Lincoln Road area is significantly warmer than other areas in the Auckland region, possibly because of urban development, but we have retained these data in our analyses because vineyards are located there.

Vineyard locations in these two regions have not all been georeferenced, and the spatial dataset is therefore incomplete, but it shows some general trends. More than 90% of the plantings in the Auckland region are located on alluvium, and more than 7% are located on greywacke (Fig. 9a). More than 90% of the plantings in the Auckland region experience a warm-temperature climate, very high solar radiation, and moderate annual water deficits. Vineyards in the Auckland/ Northland area are generally planted on flat land, with only 14% planted on slopes equal to or greater than 3°, and no vineyards in the database are planted on land with a slope greater than 5° (Fig. 4). With such minimal slope, aspects in the region are widely distributed, and east-, southeast- and south-facing vineyards occupy more than 70% of plantings in the area.

Canterbury

Canterbury has 272 ha of plantings (Table 1), which mainly consist of Pinot Noir, Chardonnay and Riesling

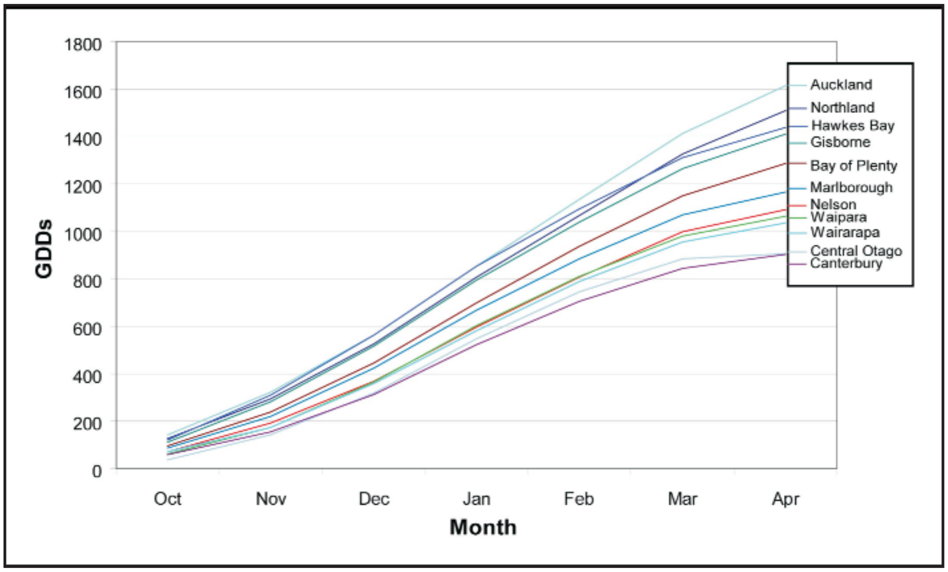

Figure 7. Cumulative growing degree days (base 10°C) for the main winegrowing regions in New Zealand during the growing season (NIWA National Climate Database: http://cliflo.niwa.co.nz/; this study).

Table 3. Planted land area and trophy winning wines in selected New Zealand wine competitions, shown as percentages of total vineyard area and trophies, respectively (NZWG 2006; http://www.wineshow.co.nz).

Rank	Region	% of plantings	% of trophies	# of trophies	Ratio
1	Nelson	3.2%	7%	7	2.22
2	Hawkes Bay	19.7%	37%	37	1.88
3	Waikato/Bay of Plenty	0.7%	1%	1	1.47
4	Auckland	2.2%	3%	3	1.35
5	Central Otago	5.7%	5%	5	0.88
6	Marlborough	52.0%	39%	39	0.75
7	Waipara	3.0%	2%	2	0.68
8	Wairarapa	3.5%	2%	2	0.57
9	Gisborne	8.7%	4%	4	0.46
10	Canterbury	1.2%	0%	0	0.00
11	Northland	0.1%	0%	0	0.00

(Fig. 8c). With 930 GDDs, an average temperature of 14.4°C during the growing season, and LTI values of IB-IC, this region is the second coolest in New Zealand (Fig. 7; Table 2). More than 85% of the vineyards are characterized by a cool climate with moderate solar radiation, moderate vapour pressure deficits and moderate annual rainfall deficits. Undulating plains and imperfectly drained soils of moderate fertility are prominent. Almost half of the vineyards are underlain by locally siliceous substrate (sandstone, limestone, siltstone), and roughly 43% on calcareous siltstone and limestone (Fig. 9b). Half of the vineyards are located on slopes of 1° or less, whereas 33% occur on moderately sloping land (3°-5°) (Fig. 4). The dominant aspects in the region are southeast (33%), north (17%), northwest (17%) and east (17%).

Central Otago

Central Otago has 1251 ha of vineyards (Table 1), and more than 75% of that area is planted in Pinot Noir (Fig. 8d). Central Otago is the coolest region, having GDDs ranging from the high 700s in Wanaka to the low 1000s in the Bendigo area. Although Bendigo has an LTI of 272 (region IC), other sites such as Clyde, Cromwell, Earscleugh, Northburn and Wanaka are in the cooler IB region. Average growing season temperatures range from 13.7°C in Wanaka to 14.9°C in Bendigo. Plantings in Otago are mainly located on Otago Schist (49%) and aggradation (glacial) gravels (44%) (Fig. 9c). Soils are generally moderately fertile. Vineyards experience cool to mild temperatures and moderate solar radiation. Moderate to high annual water deficits make irrigation in the region more likely than in areas such as Auckland, where water deficits are much lower.

Central Otago contains the largest number of vineyards planted on slopes greater than 5°. Almost 1/3 of vineyards (31%) are on steep slopes (≥5°), whereas 26% occur on moderate slopes of 3°-5° (Fig. 4). Only 2% of vineyards are on flat land with no aspect value, and less than 30% of vineyards have a slope of 1° or less, which differs markedly from the slopes that host most vineyards elsewhere in New Zealand. In this marginal climate, more than 60% of the vineyards face northeast, north and northwest, in order to maximize solar radiation (Fig. 5b).

Gisborne

Gisborne is primarily a Chardonnay-growing region, and roughly 57% of the 1911 ha under vine (Table 1) feature this variety (Fig. 8e). The digital dataset of vineyard locations in this region is incomplete and the geology, climate, aspect and slope values can be used as general guides only. This intermediate region has an average of less than 1400 GDDs and an average growing season temperature of 16.7°C. All vineyards in the dataset are located on alluvium derived from relatively soft Cenozoic rocks, so gravel is rare. The climate is warm, solar radiation is high, and annual water deficits are moderate. The landscape consists of flat floodplains and gently undulating plains underlain by poorly to imperfectly drained soils of low to moderate fertility. Vineyards are located on flat land having slopes of less than 1°.

Hawkes Bay

Hawkes Bay is the second largest winegrowing region and has a total of 4341 ha under vine (Table 1), half of which is Chardonnay and Merlot (Fig. 8f). The region has about 1400 GDDs and an average growing season temperature

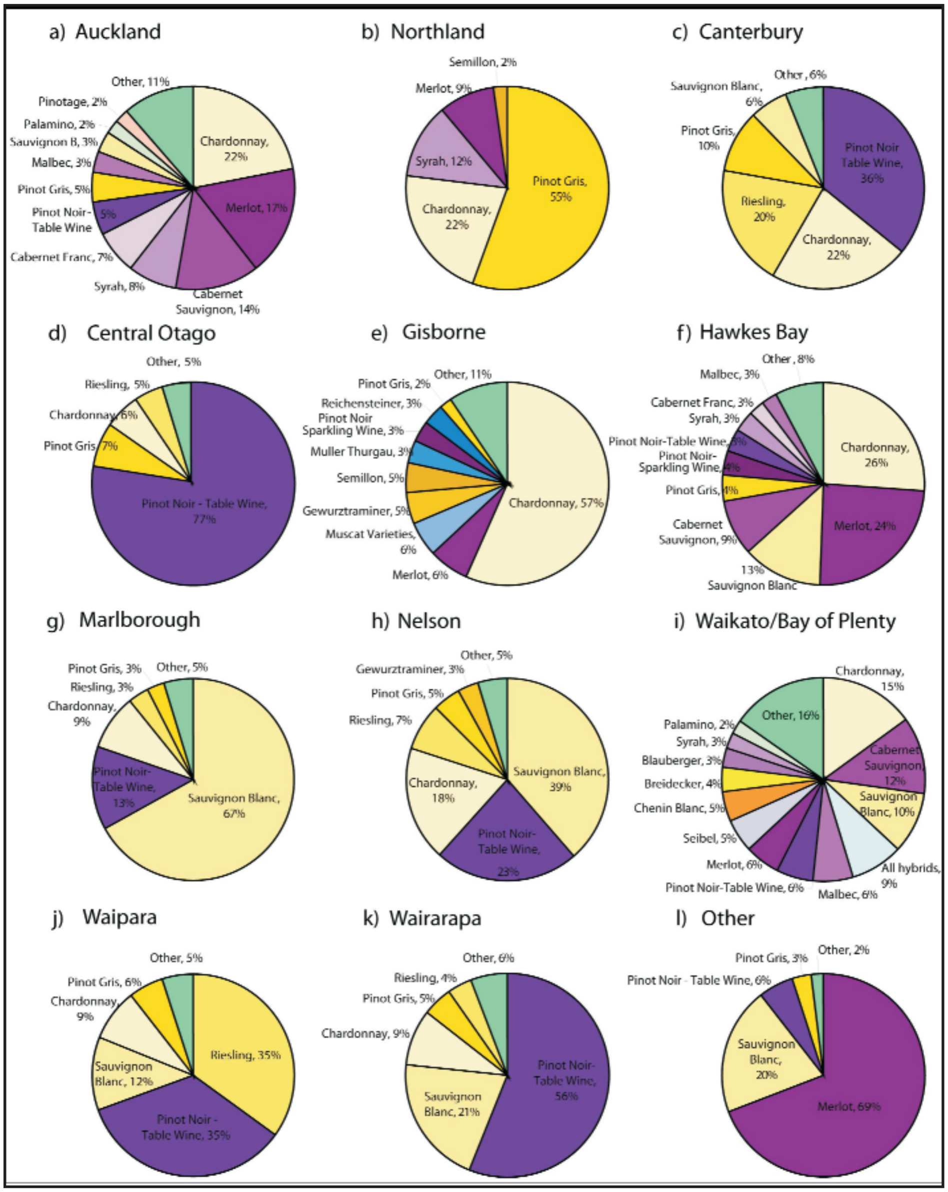

Figure 8. Grape varieties planted in New Zealand winegrowing regions as a percentage of regional total hectares (NZWG 2006).

of 16.7°C (Table 2; Fig. 7). Approximately 63% of plantings are on aggradation (glacial) gravels, and 31% on marine gravel/sand/silt (Fig. 9d). Plantings benefit from a warm climate, high solar radiation and moderate to low annual water deficits. Landforms mainly consist of flat flood plains and undulating hills of moderate to low fertility and imperfect drainage. The Gimblett Gravels winegrowing district is located in Hawkes Bay, and may be the first such viticultural appellation in the New World to be defined strictly by a distinct soil boundary. The designation follows a defined boundary of roads and rivers and contains mainly Omahu soils, which comprise a fine-grained sand to loamy sand topsoil overlying stony gravels mixed with varying proportions of sand. The ca. 800 ha district is now fully planted in mainly red varieties (Gimblett Gravels Winegrowers Association (GGWA) 2009). Because of the Hawkes Bay region's extensive plantings on gravel, 85% of vineyards occur on slopes of 1° or less (Fig. 4), and 50% are on flat land with no aspect (Fig. 5c).

Marlborough

Marlborough, the largest viticultural region in New Zealand, has 11 476 ha of plantings (Table 1), 67% of which consists of Sauvignon Blanc (Fig. 8g). The region has approximately 1165 GDDs (Fig. 7) and an average growing season temperature of 15.5°C (Table 2). Temperatures are generally mild, and solar radiation levels are high to very high. Most vineyards are located on undulating plains and flat flood plains that have moderate to high annual water deficits. Soils are generally well drained and are moderately to highly fertile, although some smaller areas are characterized by imperfect drainage and low fertility. More than 75% of vineyards are located on alluvium and gravels (Fig. 9e). More than three-quarters (77%) of the vineyards are on flat land, and in 93% of the vineyards slopes are less than or equal to 2° (Fig. 4). Aspect calculations indicate that 48% of vineyards show no aspect value because they are planted on very flat land (Fig. 5d), underlining the predominance of flat topography in New Zealand vineyards.

Nelson

The Nelson region has 695 ha planted (Table 1), 39% of which is Sauvignon Blanc (Fig. 8h). Nelson has approximately 1112 GDDs (Fig. 7) and an average growing season temperature of 15.3°C (Table 2). However, the vineyard location dataset for the region is incomplete, and these data should therefore be used as general guides only. Plantings experience a mild climate, moderate solar radiation, and low annual water deficits. The standard deviation of average growing season temperature is the lowest in the Nelson region, indicating that this area has the most stable climate of all winegrowing regions of New Zealand. The area features undulating plains and hills underlain by well drained, low-fertility soils derived from coarse gravels; plantings are situated on piedmont gravels, on flat land facing slightly northwest (Fig. 4).

Waikato/Bay of Plenty

A large number of varieties are planted in the Waikato/Bay of Plenty area (Fig. 8i), which has total plantings of more than 150 ha (Table 1). The region has approximately 1068 GDDs (Fig. 7) and an average growing season temperature of 16.1°C (Table 2). The vineyard dataset for the region is incomplete, and should be used as a general guide only. Plantings in the region are located

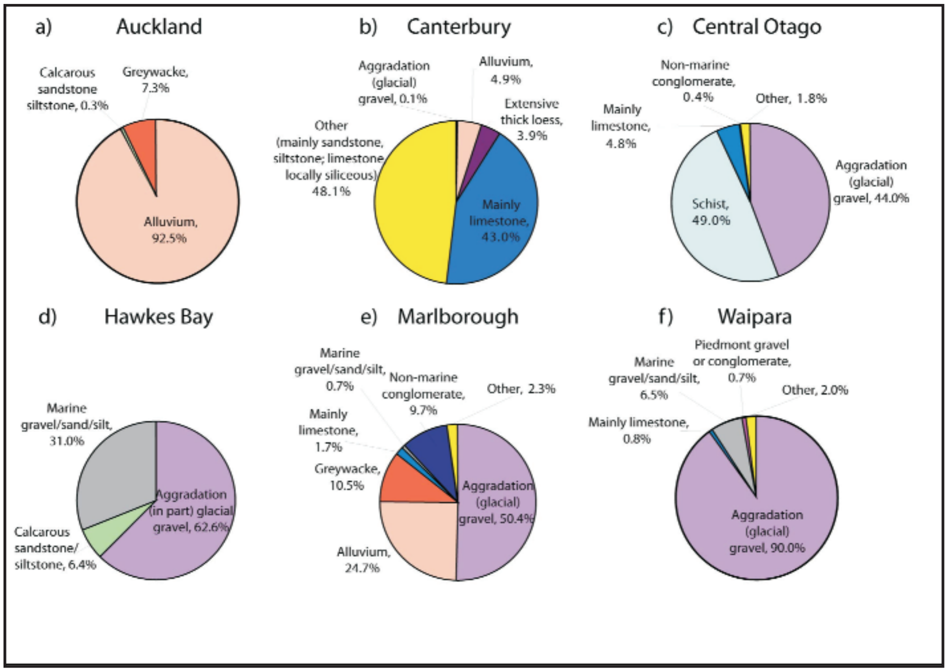

Figure 9. Geological units that underlie vineyards in New Zealand winegrowing regions, expressed as percentage of total vineyard area in each region (geological data of New Zealand was sourced from GNS Science; this study).

mainly on pumiceous pyroclastic deposits that are a product of Quaternary volcanism. The area is generally warm, and features high solar radiation and low annual water deficits. Gently sloping land is dominant; soils are generally well-drained, of low fertility, and derived mainly from rhyolitic alluvium and tephra. Vineyards are located on moderate slopes of 3°-5° (Fig. 4) and have a northwest aspect.

Waipara

Waipara has 652 ha under vine (Table 1) and is a rapidly growing area. The two main varieties in the Waipara region are Pinot Noir (35%) and Riesling (35%) (Fig. 8j). GDDs during the growing season are approximately 1038 (Fig. 7) and the average growing season temperature is 14.9°C (Table 2). The area can accumulate up to 100 more GDDs than other areas of Canterbury because hills shelter it from the cool coastal northeasterly winds (Schuster et al. 2002). Plantings are located mainly in areas that have a mild climate, high solar radiation and moderate annual water deficits. Soils are generally highly fertile but imperfectly drained; parent materials mainly consist of greywacke gravels and some loess and fine alluvium, and most plantings (90%) are underlain by gravels (Fig. 9f). Slopes are less than 1° in almost half (46%) of the vineyards in the region, but when compared to the New Zealand average, a higher proportion of vineyards in this region are planted on steeper slopes (Fig. 4). An unusually large number (28%) of vineyards face southeast (Fig. 5e).

Wairarapa / Wellington

Plantings in the Wairarapa/Wellington area total 776 ha (Table 1), and Pinot Noir is the prominent variety (Fig. 8k). The region has approximately 1033 GDDs and an average growing season temperature of 14.9°C (Table 2). The flat plains where 56% of vineyards are planted are characterized by warm temperatures, high solar radiation, generally low fertility, moderate vapour pressure deficits and low to moderate annual rainfall deficits. All of the plantings are located on alluvium; however, the digital dataset for the region is incomplete and should be used for general information only. Vineyards are generally located on the flat floodplains of the Manawatu River; most have slopes of less than 1° (Fig. 4), and over half (57%) face northwest.

Other

New Zealand has other vineyards that are not located in any of the above major regions (Fig. 8l). These are mainly devoted to Merlot and make up only 0.1% of vineyard land in the country.

DISCUSSION

This section discusses the soils and rocks that underlie New Zealand vineyards, and how this relates to soil temperature, root penetration, slope, aspect, vigour, yield, and water supply. We also discuss the five major varietals grown in New Zealand (Chardonnay, Pinot Gris, Pinot Noir, Riesling and Sauvignon Blanc), as well as how the wine industry may evolve in the future.

Geology, Soils and Wine

The physical nature of the soil may have the most notable effect on wine quality because of its effect on drainage, water uptake and temperature regulation (Berry 1990; Saayman 1992). Soil texture is important to viticulture, influencing the water holding capacity, root growth and overall vigour (Rice 2002). Soils in New Zealand normally exhibit low to moderate fertility, and since most vineyards are located on free-draining gravels, irrigation typically controls water uptake and availability. These soils tend to be better regulators of root-zone temperature because the gravels absorb heat during the day and slowly release it at night. Hard soil reduces root growth and water/nutrient uptake, whereas soils containing biopores and fissures lead to root clumping, making it more difficult for roots to access interstitial soil minerals (Passioura 1991; Hinckley et al. 2008).

Some regions in New Zealand are known for producing premium types of a particular wine. For example, Marlborough is known for producing premium Sauvignon Blanc and Pinot Noir, Waipara for Riesling and Pinot Noir, and Hawkes Bay consistently produces award-winning red and red blends such as Merlot, Malbec, Syrah and some Cabernets. The vines grown in these areas are predominantly situated on gravels. Worldwide, some vineyards located on alluvium produce premium wines (e.g. Meinert and Busacca 2000, 2002), but in other areas, such as the *Côte de Nuits* and *Côte de Beaune* vineyards in Burgundy, no red

Grand Cru vineyards are located on alluvial soils (Wittendal 2004). Therefore, the New Zealand industry may benefit by increasing the diversity of soil types where grapes are planted; more research on this subject is needed in a New Zealand context.

The Central Otago region is experiencing rapid growth and increased plantings of Riesling, Pinot Noir, Pinot Gris and Chardonnay. Many of these new sites are being developed on Otago schist, which is unique to the region. Some Riesling and Pinot Noir wines produced from plantings on schist exhibit a characteristic pepper or gunflint aroma similar to that noted in wine from vineyards underlain by schist in France (Berry 1990). Regional wine styles may be influenced by increasing the number of vineyards located on schist, more research is needed to determine how grape characteristics will be influenced by soil type in the region.

Regions such as Hawkes Bay that typically blend red wines may benefit from planting on different soil types in order to increase the blending options and allow for the production of different styles of blended wines. Berry anthocyanin concentration and berry weight can be influenced by soil type, and some red wines can be distinguished based on soil type alone (e.g. Van Leeuwen et al. 2004; Elliot-Fisk 1993). Vineyards in Hawkes Bay are largely planted on free-draining soils and are commonly irrigated, allowing for better control of water supply to the vines.

Soil Temperature and Root Penetration

Soils that warm early in the season and retain heat have the potential to produce premium grapes in an otherwise too-cool climate. Soil temperature correlates with vegetative cycle (Tesic et al. 2001), total acid content of the must, and wine colour (Dutt et al. 1981); an increase in root temperature produces an increase in vine growth, brix (a measure of the sugar content of grapes), pH, praline (an amino acid) and K (Zelleke and Kliewer 1979). Based on climate data alone, regions such as Northland and Auckland should be able to produce premium red wines such as Merlot and Malbec. Many of the trophy-winning wines of these varieties, however, are best grown in regions that have stony soils, such as the Gimblett Gravels in Hawkes Bay, as plantings in that area can experience several degrees warmer than its surroundings. Plantings in the Gimblett Gravels area can experience temperatures that are 2-3°C warmer than surrounding areas on a typical Hawkes Bay summer day (GGWA 2009).

A good soil will allow for the full but slow maturation of cultivars towards the end of the growing season (Seguin 1986; Deloire et al. 2005). Because the roots and above-ground part of a grapevine respond differently, soils that warm more quickly in the spring generally have a growth advantage by encouraging root growth even though the visible part of the plant remains relatively dormant. Early warming is a common feature of good terroirs, and is especially valuable in cool climates (Jackson 2001). Light and stony soils are amongst the quickest to warm up, whereas heavy clays take longer. Pebbles and rocks in the soil absorb heat during the day and promote slow cooling at night, resulting in warmer evening temperatures (Wright 2001). Selecting the right aspect and stony soils that retain heat can add up to an extra 200 degree-days (Jackson and Schuster 2001) and result in earlier maturation of grapevines. This may at least partly explain why trophy-winning red wines are grown in Hawkes Bay even though it is relatively cool compared to other international premium red wine-growing areas. Stony soils are also important in cool regions such as Marlborough and Waipara, where many vineyards are planted on flat land. In cool regions where vineyards expand from the valley gravels onto the hillsides, the latter areas lack the warming effect of gravels and the soils may therefore be cooler, making the choice of aspect and slope more important. The importance of early maturation in other regions may be realized with further study as the industry expands.

A healthy root system is vital for plant health and maximized grape quality. For example, in one Marlborough study block where soils range from silty loam to gravel, areas with gravelly soils have grapevines with extra-small trunk circumferences, greater numbers of fine roots, and greater root density. The gravelly soils also have higher soil temperatures, and the extra-small vines produce fruit that ripens earlier and is higher in quality than fruit growing on larger vines on silty loam soils (Trought et al. 2008).

Slope and Aspect

Approximately 57% of the vineyards in New Zealand that are not located on flat land are planted on slopes facing northwest, north or northeast, which provides maximum solar exposure in the southern hemisphere. Vineyard rows are generally oriented north-south to maximize solar radiation and distribute it equally to both sides of the vines. Slope can alter the effects of orientation and should ideally be perpendicular to the direction of solar radiation so as to maximize sunlight interception and increase heat accumulation (e.g. Galet 2000; Jackson 2001). By planting on slopes it is also possible to increase drainage after heavy rains (Jackson 2001), although this may not be as relevant in the New Zealand wine industry because many vineyards are located in drier regions, on flat, free-draining soils.

Variables such as wind direction and wind frequency may also play a role in determining how vineyards are planned; hence, premium wines may not necessarily come from vineyards whose slopes face north or south. In Waipara, more than 40% of vineyards in the region face southeast, south or southwest. Although these aspects may appear to be in the wrong direction, the planting of many of these vineyards was based on the location of soils developed on limestone, even where these areas face south. It may be valuable for the New Zealand wine industry to experiment with different aspects in different regions to help quantify relationships among geology, soils, and aspect in different areas.

Many of the trophy-winning wines in New Zealand were produced from grapes grown in vineyards that use management practices aimed at controlling yield in order to maximize quality. However, some grape varieties, such as Sauvignon Blanc, are modelled on large yields and the vineyards are highly mechanized, making planting on flat land essential. Because of the increased production costs, plantings on steeper hillsides where vineyard management is less mechanized may not be economically feasible for New Zealand Sauvignon Blanc. In contrast, Central Otago, the coolest winegrowing region in New Zealand, has more vineyards planted on steeper slopes (>5°) than any other region (Fig. 4). These vineyards are managed primarily by manual labour, and the slopes are steep by New Zealand standards, but in other vineyards worldwide, slopes of 15-40° are not unheard of (e.g. Wilson 1998). As the Central Otago region continues to grow, more vineyards may be planted on steeper slopes and consequently different geology, which may have an influence on local wine styles. Pinot Noir from such areas is commanding high prices on the international market, so increased production costs and low yields can therefore be justified.

As the New Zealand wine industry continues to expand, more vineyards will be planted on hillsides, and decisions about aspect and slope will become more significant. Although north-facing slopes may be favoured in many areas, factors other than sunlight interception and heat accumulation can be important site selection criteria, as demonstrated in other winegrowing regions worldwide (e.g. Wilson 1998; Galet 2000; Wittendal 2004).

Vigour and Yield

Yield and variation in vine vigour commonly match changes in local soil properties, which in turn can influence grape characteristics. For example, in Cabernet Sauvignon and Ruby Cabernet vineyards in Australia, variations in colour and phenolics correlate with areas of different yield, and yields correlate with variations in soil properties, particularly the amount or location of clay in the soil profile (Bramley 2001, 2005). Similarly, work in an Ontario Riesling vineyard shows that vine vigour and soil texture have an influence on berry, must and wine composition (Reynolds et al. 2007). Research at Orlando Wines of South Australia has shown that soil variation in a particular irrigation block had a direct impact on variation in grapes delivered to the winery (Smart 2002). Areas of decreasing vigour in an Oregon Pinot Noir block showed significant increases in proanthocyanidin, epigallocatechin, pigmented polymer concentrations, and skin tannin extraction to the wine (Cortell et al. 2005).

In New Zealand, vine trunk circumference measurements are commonly used as a proxy for grapevine vigour (Trought 1996). Although more work is required, the available data clearly demonstrate that vine trunk circumference correlates with soil texture and electromagnetic signatures that reflect varying soil characteristics (e.g. Mills 2006; Imre et al. 2007; Trought et al. 2008). Ongoing work is designed to test how these variations correlate with attributes of the grapes and resulting wines.

In vineyards where variation exists in yield and/or vigour, alternative management practices can be used to achieve more uniform grape characteristics by differential harvesting and storing of grapes with different properties in separate bins (Smart 2003). Vineyards can be divided into separate management zones, based largely on either yield variation or soil type, in order to produce more grapes with desired properties throughout the vineyard (Smart 2002).

Water Supply

Although some areas receive very large amounts of rain, most New Zealand vineyards are located in areas with relatively little rainfall. Many vineyards planted on free-draining gravels are irrigated; free-draining soils are often preferred because irrigation allows water availablity to the vines to be better controlled, and there is little need for the soil to mitigate the effects of drought. Vineyards planted on alluvium and aggradation gravels on valley floors in regions such as Marlborough and Hawkes Bay have different properties than vineyards where soils have developed on sandstone, siltstone and limestone hillsides. Therefore, as plantings expand up these hillsides, water-holding capacity and resulting water supply to the vines will vary according to substrate characteristics. Irrigation design and site selection will have to take these subsurface characteristics into account.

Climate Characteristics in New Zealand Winegrowing Regions

In general, trophy-winning, cooler varietal wines such as Pinot Noir and Riesling are produced in regions with average growing-season temperatures similar to those in other winegrowing regions worldwide. Warmer-weather varietals such as Merlot and Malbec, however, are typically produced to premium standard in regions that are cooler than the international norm. This is explained by the predominance of gravely soils that warm early and retain heat, allowing grapes to ripen in an otherwise too-cool climate, as in the example given previously of the Gimblett Gravels region in Hawkes Bay. As the New Zealand wine industry expands, a more detailed understanding of local site characteristics may lead to increased success in the production of ultra-premium wines.

FUTURE OF THE NEW ZEALAND WINE INDUSTRY

Site selection in New Zealand's traditionally flat winegrowing regions is expanding to hillsides where few grapes are currently grown. Alluvium and aggradation gravels were, and in many cases still are, the preferred choice for new vineyard establishment because of their free-draining nature, which is ideal where vineyards are irrigated. Most of the industry's growth has occurred in Marlborough, which has more than 50% of total New Zealand acreage and primarily produces Sauvignon Blanc. This sector of the industry features high-yielding crops and is highly mechanized, allowing large vineyards to be managed efficiently. But prime viticultural land in New Zealand is becoming scarcer, and what remains tends to be extremely expensive, making entry into the market on these lands very costly. The New Zealand wine industry, however, continues to grow. With less alluvium and aggradation gravels now available for planting, the industry is directed towards growth on different soil types and increased plantings on slopes. Although we expect that this will affect the properties of grapes grown on these sites, the exact implications are far from clear.

Sauvignon Blanc makes up more than 50% of New Zealand production even though New Zealand trophy-winning Sauvignon Blanc is grown in areas that are cooler than in other major winegrowing regions of the world (Fig. 6b). Most (more than 90%) of the trophy wines that are produced in Marlborough are located on irrigated alluvium and aggradation gravels. Marlborough produces a good-quality Sauvignon Blanc at a reasonable price, with particularly high concentrations of compounds responsible for both passionfruit/grapefruit and capsicum aromas (Nicolau et al. 2006). Producing wines from grapes grown on soils developed over greywacke, argillite, sandstone, siltstone or limestone bedrock will likely yield different results, and the potential for producing very different wines.

Chardonnay accounts for approximately 17% of New Zealand wine-grape production. It is expected to continue a downward trend in share of national production, but to increase in the Central Otago region. Chardonnay can be grown successfully in many different climates and soil types, each producing distinct characteristics in the wines (Berry 1990). Marlborough Chardonnay is similar to the Australian fruit style, but with a little extra acidity. Grapes used in New Zealand trophy-winning Chardonnays are typically grown in areas that are slightly warmer than other Chardonnay-producing areas globally (Fig. 6b). The versatility of this grape is shown by the fact that trophy Chardonnays are located in four different winegrowing regions, more than any other varietal in New Zealand. Many of the trophy-winning Chardonnay grapevines are located on alluvium and aggradation gravels surrounded by hills underlain by greywacke or calcareous sandstone and siltstone; hence, in the future, vineyards may produce premium, yet distinctly different wines from these adjacent hillside blocks. Cooler areas such as Central Otago show potential for growing distinct and ultra-premium Chardonnays on schist-based soils.

Pinot Noir accounts for roughly 12% (by weight) of the grapes harvested in New Zealand. GDDs in areas such as Beaune, Burgundy (1333 GDDs), the Côte d'Or (1180 GDDs) and most Pinot Noir regions in North America (1333-1444 GDDs) (Haeger 2004; Jackson and Schuster 2001) are comparable to regions in New Zealand that produce premium Pinot Noir, such as Marlborough, Central Otago, Waipara and the Wairarapa (<1200 GDDs). Current plantings of premium Pinot Noir are located mainly on gravels, similar to what is found in North America, but unlike some premium Pinot Noir-producing areas such as Burgundy. Because the soil may have an overall influence on grape characteristics, further experimentation is needed to determine how the expansion of plantings onto different soil types will affect quality in a New Zealand context.

Merlot accounts for 6% of total tonnage harvested in New Zealand. Some of New Zealand's premium reds are produced in areas underlain by large quantities of gravel. Hawkes Bay, for example, is home to several trophy-winning red Cabernet Merlot Malbec blends, as well as single varietal wines such as Merlot, Malbec and Syrah. The Gimblett Gravels winegrowing district in the Hawkes Bay region has won trophies for reds such as Syrah, Merlot and Tempranillo, although this area is cooler than those producing premium reds elsewhere in the world (Fig. 6a). Approximately 18% of plantings in the Hawkes Bay region are located in the Gimblett Gravels designation, yet the latter accounts for more than 50% of trophy-winning wines in Hawkes Bay, indicating the success of planting on gravels in this region. In Hawkes Bay, areas underlain by marine sandstone/siltstone, greywacke and limestone could also be planted. The resulting wine styles likely will be different than those grown on gravels, which could increase blending options. Lower ripening capacity of new sites on hillsides may be compensated by careful attention to microclimate and by various canopy management techniques.

Riesling accounts for approximately 4% of total production in New Zealand. The regions producing trophy-winning Rieslings feature cool to intermediate growing-season temperatures, which is to be expected of this variety. Most Riesling is produced on alluvium and aggradation (glacial) gravels in Marlborough; this substrate may, at least in part, be responsible for the variation in Riesling styles compared to Central Otago schist sites. Plantings in the latter area typically produce wines that may emulate sweet, high-acid, Mosel-style wines. Some Central Otago wines produce a characteristic gunflint aroma whereas others have more of a citrus and floral style.

The above-mentioned five varietals are responsible for almost 90% of New Zealand wine production. The diverse climate and soil types in New Zealand winegrowing regions, however, may have potential for other premium varietals to be grown to a high standard. Some varieties such as Blauburger, Limberger, Durif, and Gamay Noir show promise in the production of bulk wines (Wood 1995), but the New Zealand industry must focus on producing wines of quality rather than quantity. Studies are needed to address the quality potential of other varietals; the available georeferenced climate and subsurface data, combined with the current state of knowledge relating to ideal conditions for certain varietals, should make this task more achievable.

CONCLUSIONS

This research looks at the terroir of New Zealand vineyards in 2006-2007. More than 70% of vineyards in New Zealand are located on alluvium and gravels, and these free-draining subsurfaces have long been the preferred location for vineyards. Subsurface properties have an effect on grape characteristics (e.g. Van Leeuwen et al. 2004; Macqueen and Meinert 2006; Reynolds et al. 2007; Trought et al. 2008), and the continued expansion of the industry onto new soil types with differing aspects and slopes will affect resulting grape and wine characteristics. Currently, only 7% of vineyards are located on slopes greater than 5°, which is in contrast to many premium international winegrowing regions. Many cooler varietals are grown in climates similar to those producing quality wines internationally. Award-winning reds, however, tend to be grown in cooler regions, presumably because many of these vineyards are located where gravely soils retain heat and increase local GDDs. This research provides a platform for improved understanding of the environmental characteristics of many New Zealand vineyards and also provides baseline data for tracking how the industry expands in the coming years. Improvements in the national vineyard database combined with detailed studies of local and regional terroir may significantly enhance the ability of the New Zealand wine industry to understand factors that contribute to regional wine styles, and may help the industry continue to produce ultra-premium wines.

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REFERENCES

Amerine, M.A., and Winkler, A.J., 1944, Composition and quality of must and wines of California grapes: Hilgardia, v. 15, p. 493-675.

Berry, E.M., 1990, The importance of soil in fine wine production: Journal of Wine Research, v. 1, p. 179-194.

Bowen, P.A., Bogdanoff, C.P., Estergaard, B.F., Marsh, S.G., Usher, K.B., Smith, C.A.S., and Frank, G., 2005, Geology and Wine 10: Use of geographic information system technology to assess viticultural performance in the Okanagan and Similkameen Valleys, British Columbia: Geoscience Canada, v. 32, p. 161-176.

Bramley, R.G.V., 2001, Progress in the development of precision viticulture — variation in yield, quality and soil properties in contrasting Australian vineyards, *in* Currie, L.D. and Loganathan, P., *eds*., Precision Tools for Improving Land Management: Occasional Report No. 14, Fertilizer and Lime Research Centre, Massey University: Palmerston North, New Zealand, p. 25-43.

Bramley, R.G.V., 2005, Understanding variability in winegrape production systems 2. Within-vineyard variation in quality over several vintages: Australian Journal of Grape and Wine Research, v. 11, p. 33-42.

Bramley, R., Pearse, B., and Chamberlain, P., 2003, Being profitable precisely — a case study of precision viticulture from Margaret River: The Australian & New Zealand Grapegrower and Winemaker, Annual Technical Issue 2003, p. 84-87.

Carey, V.A., Bonnardot, V.M.F., and Knight, F., 2003, The zoning of terroirs for wine production: South Africa, *in* Fregoni, M., Schuster, D., and Paoletti, A. *eds*., Terroir zonazione viticoltura: Trattato internazionale: Phytoline (Rivoli Veronese), Verona, Italy, p. 227-244.

Chitkowski, R.L., and Fisher, J.R., 2005, Effect of soil type on the establishment of grape phylloxera colonies in the Pacific northwest: American Journal of Enology and Viticulture, v. 56, p. 207-211.

Cortell, J.M., Halbleib, M., Gallagher, A.V., Righetti, T.L., and Kennedy, J.A., 2005, Influence of vine vigour on grape (Vitis vinifera L. Cv. Pinot Noir) and wine proanthocyanidins: Journal of Agricultural and Food Chemistry, v. 53, p. 5798-5808.

Deloire, A., Vaudour, E., Carey, V., Bonnardot, V., and van Leeuwen, C., 2005, Grapevine responses to terroir: A global approach: Journal International des Sciences de la Vigne et du Vin, v. 39, p. 149-162.

Dutt, G., Mielke, E.A., and Wolfe, W.H., 1981, The use of soils for the delineation of viticultural zones in the four corners region: American Journal of Enology and Viticulture, v. 32, p. 290-296.

Elliot-Fisk, D.L., 1993, Viticultural soils of California, with special reference to the Napa Valley: Journal of Wine Research, v. 4, p. 67-77.

Galet, P., 2000, General Viticulture. Translated by John Towey, Oenoplurimédia, France, 443 p.

Graham, I.J., *ed*., 2008, A Continent on the Move (New Zealand Geoscience into the 21st Century): Geological Society of New Zealand in association with GNS Science, Wellington, New Zealand, 377 p.

GGWA (Gimblett Gravels Winegrowers Association), 2009, Gimblett Gravels: [http://www.gimblettgravels.com]

Haeger, J.W., 2004, North American Pinot Noir: University of California Press, Los Angeles, 445 p.

Hinckley, E.S., Kendall, C., and Loague, K., 2008, Not all water becomes wine: Sulfur inputs as an opportune tracer of hydrochemical losses from vineyards: Water Resources Research, v.44, W00401, doi: 10.1029/2007WR006672.

Imre, S.P., Mauk, J.L., Bell, S.C., and Dougherty, A.J., 2007, Correlations among ground penetrating radar, electromagnetic induction and vine trunk circumference data: Towards quantifying terroir in New Zealand Pinot Noir vineyards: GESCO (Groupe d'Etude des Systèmes de Conduite de la Vigne) Proceedings, 2, Porec, Croatia, June, 2007, p. 1392-1398.

Jackson, D., 2001, Monographs in cool climate viticulture No. 2: Climate: Daphne Brasell Associates Ltd. with Gypsum Press, Wellington, 80 p.

Jackson, D., and Schuster, D., 2001, The Production of Grapes and Wine in Cool Climates: Gypsum Press and Daphne Brasell Associates Ltd., Wellington, New Zealand, 193 p.

Johnson, L., Lobitz, B., Armstrong, R., Baldy, R., Weber, E., De Benedictis, J., and Bosch, D., 1996, Airborne imaging for vineyard canopy evaluation: California Agriculture, v. 50, p. 14-18.

Johnson, L., Roczen, D., and Youkhana, S., 2001a, Vineyard canopy density mapping with IKONOS satellite imagery: Third International Conference on Geospatial Information in Agriculture and Forestry, Denver, Colorado, Nov. 5–7, 2001.

Johnson, L.F., Bosch, D.F., Williams, D.C., and Lobitz, B.M., 2001b, Remote sensing of vineyard management zones: Implications for wine quality: Applied Engineering in Agriculture, v. 17, p. 557-560.

Johnson, L.F., Roczen, D.E., Youkhana, S.K., Nemani, R.R., and Bosch, D.F., 2003, Mapping vineyard leaf area with multispectral satellite imagery: Computers and Electronics in Agriculture, v. 38, p. 33-44.

Jones, G.V., 2006, Climate and terroir: Impacts of climate variability and change on wine, *in* Macqueen, R.W., and Meinert, L.D., *eds*., Fine Wine and Terroir — The Geoscience Perspective: Geoscience Canada Reprint Series 9, Geological Association of Canada, p. 203-216

Jones, G.J., Snead, N., and Nelson, P., 2004, Geology and Wine 8. Modeling viticultural landscapes: A GIS analysis of the terroir potential in the Umpqua valley of Oregon: Geoscience Canada, v. 31, p. 167-178.

Leathwick, J., Morgan, F., Wilson, G., Rutledge, D., McLeod, M., and Johnston, K., 2002, Land Environments of New Zealand: A Technical Guide: David Bateman Ltd., Auckland, 237 p.

Macqueen, R.W., and Meinert, L.D., *eds*., 2006, Fine Wine and Terroir: The

Geoscience Perspective: Geological Association of Canada Reprint Series 9, 247 p.
Martínez-Casasnovas, J.A., and Sánchez-Bosch, I., 2000, Impact assessment of changes in land use/conservation practices on soil erosion in the Penedés-Anoia vineyard region (NE Spain): Soil & Tillage Research, v. 57, p. 101-106.
Meinert, L.D., and Busacca, A.J., 2000, Geology and Wine 3. Terroirs of the Walla Walla Valley appellation, southeastern Washington State, USA: Geoscience Canada, v. 27, p. 149-171.
Meinert, L.D., and Busacca, A.J., 2002, Geology and Wine 6. Terroir of the Red Mountain Appellation, Central Washington State, USA: Geoscience Canada, v. 29, p. 149-168.
Mills, T.S., 2006, Relations among geology, soil type and Sauvignon Blanc vineyard variation in Marlborough, New Zealand: M.Sc. Thesis, University of Auckland, Auckland, 259 p.
Nemani, R., Johnson, L., and White, M., 2001, Adding science to intuition: Application of remote sensing and ecosystem modelling and management: The Australian Grapegrower & Winemaker, Annual Technical Issue, p. 45-47.
Nicolau, L., Benkwitz, F., and Tominaga, T., 2006, Characterising the aroma of New Zealand Sauvignon Blanc: The Australian & New Zealand Grapegrower and Winemaker, v. 509, p. 46-49.
NZTE (New Zealand Trade and Enterprise), 2007, [http://www.investnewzealand.govt.nz/common/files/NZTE%20Wine%20Brochure_Low%20Res%20Apr07.pdf].
Passioura, J.B., 1991, Soil structure and plant growth: Australian Journal of Soil Research, v. 29, p. 717-728.
Reynolds, A.G., Senchuk, I.V., van der Reest, C., and de Savigny, C., 2007, Use of GPS and GIS for elucidation of the basis for terroir: Spatial variation in an Ontario Riesling vineyard: American Journal of Enology and Viticulture, v. 58, p. 145-162.
Rice, T.J., 2002, Importance of soil texture to vineyard management: Practical Winery and Vineyard Magazine, March/April 2002, p. 22-30.
Saayman, D., 1992, Natural influences and wine quality, Part 2: The role of soil: WineLand, August, p. 49-51.
Seguin, G., 1986, Terroirs and pedology of wine growing: Experimentia, v. 42, p. 861-873.
Schuster, D., Jackson, D., and Tipples, R., 2002, Canterbury grapes & wines: Shoal Bay Press, Christchurch, 157 p.
Smart, R., 2002, New world responses to old world terroir: Wine Industry Journal, v. 17, p. 65-67.
Smart, R., 2003, Terroir reconsidered… the new New World approach to wine quality: Wine Industry Journal, v. 18, p. 42-43.
Tesic, D., Woolley, D.J., Hewett, E.W., and Martin, D.J., 2001, Environmental effects on cv Cabernet Sauvignon (*vitis vinifera* L.) grown in Hawke's Bay, New Zealand. 1. Phenology and characterisation of viticultural environments: Australian Journal of Grape and Wine Research, v. 8, p. 15-26.
Trought, M.C.T., 1996, The New Zealand terroir: Sources of variation in fruit composition in New Zealand vineyards: The fourth International Symposium on Cool Climate Viticulture and Enology, New York, p. 123-127.
Trought, M.C.T., Dixon, R., Mills, T., Greven, M., Agnew, R., Mauk, J. L., and Praat, J.-P., 2008, The impact of differences in soil texture within a vineyard on vine vigour, vine earliness and juice composition: Journal International des Sciences de la Vigne et du Vin, v. 42, p. 67-72.
Van Leeuwen, C., Friant, P., Choné, X., Trégoat, O., Koundouras, S., and Dubourdieu, D., 2004, Influence of climate, soil, and cultivar on terroir: American Journal of Enology and Viticulture, v. 55, p. 207-217.
Wildman, W.E., 1986, Phylloxera in Monterey County, California. I. Rate of spread in an advanced infestation: American Journal of Enology and Viticulture, v. 37, p. 115-120.
Wilson, J.E., 1998, Terroir: The role of geology, climate, and culture in the making of French wines: University of California Press, Berkeley, 336 p.
Wittendal, F., 2004, Great Burgundy wines: A principal components analysis of "La Côte" vineyards: Paper prepared for the 11th Œnometrics conference, Dijon, May 21, 2004.
Wood, P.N., 1995, New grape varieties for bulk wines ─ HortResearch Technical Report No. 95/09: The Horticultural and Food Research Institute of New Zealand Ltd., Havelock North, 33 p.
Wright, W.H.T., 2001, Sonoma County: Diverse geology/soils impact wine quality: Practical Winery and Vineyard Magazine, September/October, p. 40-49.
Zelleke, A., and Kliewer, W.M., 1979, Influence of root temperature and rootstock on budbreak, shoot growth, and fruit composition of Cabernet Sauvignon grapevines grown under controlled conditions: American Journal of Enology and Viticulture, v. 30, p. 312-317.

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