Chapter 11

# Climate Change and Grape Wine Quality: A GIS Approach to Analysing New Zealand Wine Regions

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Additional information is available at the end of the chapter

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## 1. Introduction

The influences of seasonal climate variability on the phenological dynamics of certain terrestrial communities observed mostly since the mid-20th century are seen as leading to unprecedented consequences (Richard, et al., 2009). The potential impacts of the phenomenon on the phenological development and in turn on the species composition of certain specific plant, insect, aquatic, bird and animal communities evolved in parallel over millions of years to form the existing "*make-up*" of what is referred to as the "*biodiversity*" or "*endemic species*" of these natural habitats, are depicted as significant (Peñuelas and Estiarte, 2010). Scientific research results have revealed that the recent rapid climate change effects on these systems, more specifically during the last few decades, have resulted in presently being seen "*temporal mismatch in interacting species*". Such ecological observations are even described as early *vital signs* of imminent "*regime shifts*" in the current base climate of these regions or latitudes (Schweiger, Settele, Kudrna, & Klotz, 2008: Saino, et al., 2009). On the other hand, climatologists portray the major cause for such rapid "*climate regime shifts*" and the consequent impacts on the survival of so called co-evolved species, as *anthropogenic* (Anderson, Kelly, Ladley, Molloy, & Terry, 2011). For this reason, research relating to climate change impacts on vegetation spread over landscapes, phenological development and population dynamics of susceptible communities, in some cases even with potential threat for total extinction of "*endangered species*" under future climate change, has in recent years gained enormous momentum. In fact, this unprecedented attention has also drawn greater scrutiny and controversies at never seen before proportions in a way hindering any form of formal research on the phenomenon (Shanmuganathan & Sallis, 2010).

Interestingly, many recent studies on climate change indicate "*major shifts*" in grapevine phenology within the next few decades. The potential impacts of climate change on grape berry ripening and in turn on grape crop harvests are predicted to ultimately result in beneficial in some wine regions and detrimental outcomes in others (Jones & Davis, 2000). The implications of such dramatic shifts are expected to affect the production of wine, its taste and distinction pertaining to its style especially, in the regions that are presently well-known world over for their vintages and wine labels, grapevine growers and winemakers will be challenged in continuing with their premium quality wine production. The current climate change rate is not considered as leading to regional scale relocation of vineyards or "*alarming*" at least for the time being (Ramón, 2010). However, based on recent research on climate change impacts observed in the last few decades on viticulture and vinification, especially from the results obtained by analysing grapevine vine phenology, grape berry composition and vintage quality, it is predicted that "*shifts*" in the present "*base climate regimes*" could occur within the next decade in certain major wine regions and two such regions are; the *Mediterranean* (Jones, et al., 2005: Deloire, 2006) and Australian (Web, 2006). The potential impacts are anticipated to impose: "added pressure on increasingly scarce water supplies, additional changes in grapevine phenological timing, further disruption or alterations of balanced composition and flavour in grapes and wine, regionally-specific changes in varieties grown, necessary shifts in regional wine styles, and spatial changes in viable grape growing regions" (Jones , 2007: 3). In this context, the paper looks at the effects of seasonal climate change on the quality of vintages produced from New Zealand's wine regions spread across the north and south islands of the country at a regional scale.

Grapevine that is being described as one among the most expensive cultivated crops with significant pre-historic development even with remarkable links to human civilisation is perceived to be the most vulnerable of all crops to the recent climate change. Grapevine varieties require niche climate and environmental conditions for successful cultivation, and history proves that the climate has been one among the major factors in the rise and fall of many wine regions over centuries (Jones G. V., 2004). The current climate change is increasingly becoming yet again the ultimate "*determinant*" factor for the continued existence of some presently well-established vineyards that are still able to ripen grapes to produce the world's famous premium wine labels derived from viticulture and winemaking knowledge refined over the last century. The vine-related historical manuscript sources from the *Klosterneuburg* monastery achieves consist of the recording of vine phenological events since the 16th century, the events were originally recorded to study the climate change impact on crop and wine taste over that time (Koch, Hammerl, Maurer, Hammerl, & Pokorny, 2010). This centuries-old records, and the fairly recent wine tasting and rating systems, such as Sotheby (Stevenson, 2007) and Michael cooper (Cooper, 2008), not only reveal viticulturist/ winemaker efforts to analyse climate change impacts, but also portray the wider spatiotemporal scales at which the change impacts on viticulture and vinification have been and are being studied; the former illustrates the impacts in the world's major wine regions over the last five centuries while the latter demonstrates the vintage-to-vintage variability in labelled wines produced from a vineyard or/ and major wine regions.

Interestingly, winemakers and sommeliers continue to utilise a fascinating methodology to describe the nexuses between the vintage-to-vintage rating (in wine taste pertaining to its style) and the weather conditions that ripened the grapes. The numeric rating as well as text descriptors used to describe vintages tend to correlate wine flavours to grape berry ripening temperature as well, for example, *Chardonnay* vintages produced from grapes ripened under "*cooler*" conditions within the ideal ripening temperature range, are described as possessing *lime/lemon* meanwhile, vintages from grapes ripened under warmer conditions of the range are linked to tropical *fruit/pineapple*, in the free text format of descriptors.

The wine descriptor system was originally developed to convey wine aroma, mouth feel and after taste characteristics along with numeric ratings in a 10 or 100 point scale, in an attempt to "quantify" the variability in vintage quality (Brochet, 2001). However, scientists see this form of interpretation as a rather "*subjective way of expressing wine quality*". Nevertheless, published work on sommelier capability to express cognitive specificity of chemical senses using distinctive wine descriptors and terms of *hedonic* (or personal likings) is seen as unique, consistent and even capable of discerning grape ripening weather conditions. Similar to the vintage label ratings, there are regional rating systems that are used to describe the overall vintage quality of major wine regions within a country or in the world. Such a chart can compiled "Wine Enthusiast" could be seen at (www.winemag.com/PDFs/Vintage_Chart_022011.pdf).

With that background on vintage rating systems, the studies that looked at analysing the effects of seasonal climate change on vintage-to-vintage rating (and vintage price change at wine auctions) at different scales are summarised in section 2. Section 3 presents an approach being investigated into analysing the seasonal climate change effects on vintages at a regional scale using an example of New Zealand wine production and regions identified as "world-famous", such as *Sauvignon Blanc* of Marlborough region.

## 2. Climate influences on wine vintage-to-vintage variability

The climate is considered as one of the major "*terroir*" factors when determining the quality of vintages apart from wine maker experience and capability. The studies that looked at the extent of this influence on vintages are presented in this section.

The vintage-to-vintage (inter annual) variability in local seasonal weather conditions can to a greater extent influence the grape ripening process and in turn the berry composition, such as sugar and phenols that give the specific colour, aroma and flavours to the wine. All these components when combined with winemaker talent and experience, give a unique characteristics, added finesse to the wine style produced from the winery and the end product is called the vintage i.e., 2009 *Kumeu River Mate's Vineyard Chardonnay.* Scientific research has shown that 50% of Vintage-to-vintage variability to be determined by climate and 25% from soil whereas, only 10% being attributed to factors relating to the grapevine variety or "*cultivar*" and some of such published research is discussed in this section. Meanwhile the other "*terroir*" determinants of grape wine quality are the environmental and soil related factors and they are carefully looked at associated with a site/region and these factors are given precedence when selecting a wine style for the site. Recent research efforts of *old* wine countries to unravel this old concept to improve viticulture and to further refine grape wine in style and appellation are presented here onwards.

In an interesting study by (van Leeuwen, et al., 2004), it is concluded that climate to be the major influencing factor on the berry ripening process and hence in the composition of berry components that give the unique characteristics to the end product vintage, its colour and Baume. The study was based on an analysis of all variables generally classified as "*terroir*" and "*cultiva*", and looked at the influences of both major sets of factors simultaneously on vintage-to-vintage vine development and berry composition of non irrigated *vitis vinifera* on gravelly soil (with heavy clay subsoil and sandy soil as well as water table within the reach of roots). This wine appellation and quality study included *Merlot*, *Cabernet franc* and *Cabernet Sauvignon* style wines. The climate variables used for the study were maximum and minimum temperatures, degree days (base of 10°C), sunshine hours, ETo (a Reference Evapotranspiration), rainfall, and water balance for a four year period from 1996 to 2000.

Similarly, in (Grifoni, Mancini, Maracchi, Orlandini, & Zipoli, 2006) the authors argued that the climate variation to be the main influencing factor on the vintage-to-vintage variability in vintage quality and stated that the other three i.e., grape variety, rootstock and soil type, as constants. Interestingly, in the study cultivation techniques were described as human factors, as the techniques tend to be seen as responsible for long-term variability because of the long periods required by grape growers for the adoption of any modification in production methods. Monthly or multi monthly average air temperatures and cumulated precipitation for 500 haP geopotential height (over the *Mediterranean* sea) and sea surface temperatures for northern hemisphere growing season (January to October) were the major variables used in the analysis. The other variables included in the analysis were North Atlantic Oscillation and Southern Oscillation indices. The results were found to be in consistent with some previous correlation coefficients established between wine quality and May to October air temperatures. The study concluded that the high values of the climate variables to be responsible for high temperature and dry conditions during the summer months in Italy that were generally observed to be favourable for high quality wine.

In (Ashenfelter, Ashmore, & Lalonde, 1995) the authors showed how the correlations between price and quality of vintages could be modelled with an example set of French red wines using regression techniques with data on the season weather that produced the wines of respective price (in logarithm) for different vintages of a portfolio of Bordeaux Chateau wine. Variables used in the analysis were; age of vintage and weather variables, such as temperature, (during growing season i.e., April-September), rain in September and August, rain in the months preceding to the vintage i.e., October-March, average temperature in September R2 (root mean squared error) for vintages of 1952-1980 excluding 1954 and 1956, as these wines were rare, the two vintages being considered as the poorest in the decade.

Meanwhile, in (Jones, White, Cooper, & Storchmann, 2005) climate and global wine quality factors were compared using the year-to-year variability over ten years to predict the potential vintage quality for the next five decades. Citing many earlier studies the authors of this work pointed out that the analysis of the relationships between climate variables and wine prices to be based on an underlying hypothesis that beneficial climate conditions would improve the wine quality and that in the past these had in turn led to short term price hikes. They also reflected that the unavailability of consistent price data for multiple regions and with different styles over many years to be a shortcoming for any complete analysis/ study on long term effects. They also argued that the vintage ratings to be a strong determinant of the annual economic success of a wine region based on the work of (Nemani, et al., 2001) but then went on to say that the ratings could be determinants of wine quality not necessarily a predictor based on (Ashenfelter & Jones, 2000) where ratings were described to be reflective of wine somewhat in an indirect way i.e., they had the same weather factors documented to be the determinants of the same wine quality.

Frost (2001) used pairs of liking ratings and 14 wine descriptor intensities, originally collected for analysis with statistical methodologies (partial and least square regression), and created a second map with liking ratings on the *y axis* and the sensory descriptive data of the wines on the *x axis*. The model only accounted for 25% of the variation, described to be very low. However, the authors made the following observations based on the map results: 1) some of the wine descriptors used in the analysis, such as "*leather*", and "*sour*" as exerting a *negative* effect on the preference, meaning subjects' liking scores were low for wines with these descriptors and 2) Subjects liked wines with certain descriptors, such as "*vanilla/oak*", "*canned vegetables*" and "*green olives*" over to wines with high "*buttery*" or "*berry*". As the model failed to explain the driving factors for the remaining 75% of the variation, the majority of the sample, the authors cautioned the readers of their results. Please note that the second approach was not with free text on wine taste instead used data obtained from a trained panel to rate the intensity of each of 14 wines used in the study.

## 3. New Zealand wine industry

New Zealand's (NZ) wine industry continues to grow rapidly in total grapevine cultivation area and in the production of premium wine catering to both domestic and export markets. The extremely diverse climate and environmental conditions combined with incredible enology skills enable NZ wineries to achieve fine quality wine with some unique flavours in a substantially wide range of appellations catering to global markets meeting considerably high standards. This rapid growth has in recent times led to increased interest in scientifically understanding the link between the country's climate conditions, site specific attributes, berry component formation and the overall impact on the ultimate end product wine and its quality (vintage). The section gives a summary of major New Zealand wine regions, varieties cultivated and ecological niche (described in terms of climate, environmental, soil and topographic factors) favourable for grapevine growth and different "*clutiva*" or varieties, before discussing the approach being investigated for modelling the correlations between the seasonal variability in weather conditions and vintage rating using data on related variables made available for this study.

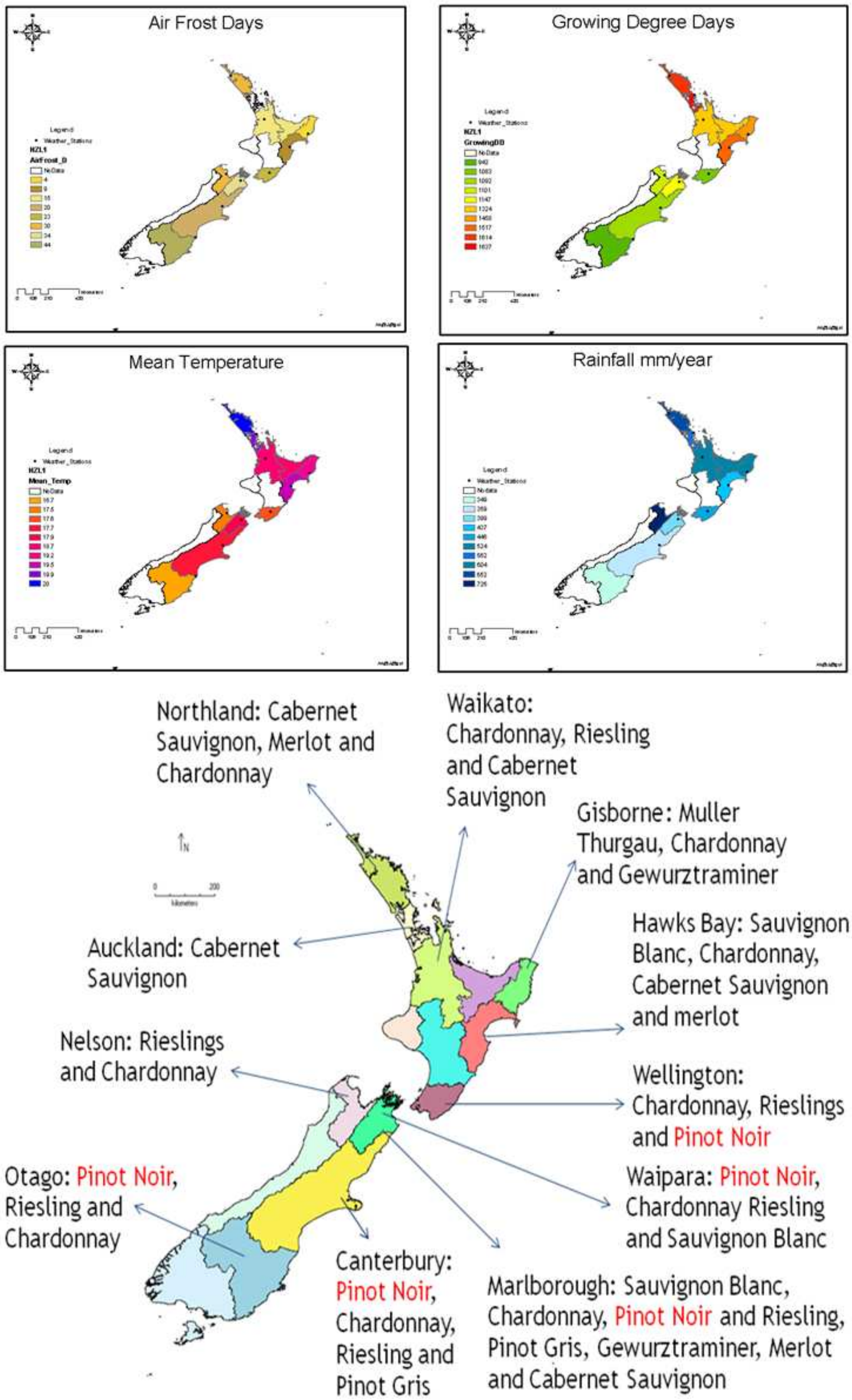



**Figure 1.** a-e: Climate variability in New Zealand's major wine regions along with different wine styles produced from the regions. For example, *Chardonnay* varieties are grown in regions of the North and South islands but not *Pinot Noir* Varieties as the latter needs extreme climate conditions i.e., cold for dormancy and high temperatures for berry ripening.

The research presented here is conducted using regional vintage ratings of white and red wine styles provided by Michael Cooper (Cooper, 2008) and climate variability extracted from National Institute of Water and Atmospheric Research (NIWA) meteorological web portal (http://cliflo.niwa.co.nz). The weather and wine quality data sets are collectively analysed using computational and formal statistical methods for map based interpretation of climate change effects on NZ wine regions, as is typical in a geographic information system (GIS) that manipulates and analyses geospatial data for informed decision making about, in this case, wine quality in relation to location and climate. The advantage of using GIS in addition to standard data analysis is the use of map-based visualisations that express spatial relationships in the data. The results of the approach experimented show interesting patterns between New Zealand's white and red wine regional vintage ratings, and certain temperature variables found to be significant by ANOVA test results across the country in the geographical context.

**New Zealand's major wine regions, climate regimes and varieties**

New Zealand is one among the *New* world wine producing countries. Its growth in fine wine production has been rather unprecedented especially over the last two decades. The country's grapevine cultivation area increased from 4,880 hectares in 1990 to 31,002 projected for 2010, with an estimated wine production of 200 Million litres (in 2008) from 582 wineries. The 2008 production consisted of 50 for domestic and 87.8 Million litres for export markets. The value of New Zealand grape wine export for 2008 was 773.9 Million dollars, 76.1 % of the export (by volume for June 2008) comprised of *Sauvignon Blanc*, the main export destinations being 34.6 % to UK, 27.6% to Australia and 21.5% to USA.

The ideal grapevine clones (wine styles) grown in New Zealand wine regions over the last ten years based on base climate are presented in figures (1a-d). The figures show the variability in air frost days/ year, growing degree days (GDD), annual mean temperature and monthly rainfall in the major wine regions of New Zealand. It is noteworthy of mention that *Chardonnay* varieties are grown in all the regions of New Zealand's North and South islands but not the *Pinot Noir* Varieties as the latter needs extreme climate conditions i.e., cold during grapevine dormancy and high temperatures for berry ripening.

## 4. The methodology for modelling wine quality using regional vintage ratings

In this research, available monthly weather variables and a complete set of regional vintage ratings (while and red wine styles) for the ten major wine regions of New Zealand are analysed using statistical and data mining methods to produce models that best fit the data and are outlined. The methodology adopted consists of the following steps:

1. Regional scale white and red vintage ratings of New Zealand's ten wine regions as presented in Michael Cooper's wine atlas (1st and 2nd editions) from 1993 to 2006 are compiled in to one data file. The ten well-known NZ wine regions included are: Auckland 1, Canterbury 2, Gisborne 3, Hawks Bay 4, Marlborough 5, Nelson 6, Northland 7, Waikato 8, Wairarapa 9, Central Otago 10.

2. The original regional vintage ratings 2-7 for white and red wine styles are reclassified into binary 1(2-5) and 2(6&7) for ANOVA analysis with available weather data. The weather data extracted from NIWA is compiled to match each of the NZ regional vintage rating relating to white and red wines. Hence, each regional vintage rating is combined with a set of climate variables covering its grapevine growing season (12 months prior to harvest). The 14 monthly weather variables used in the ANOVA tests over the growing season (May – April) are listed below:
   a. Rainfall
   b. Mean Air Temperature
   c. Extreme Maximum Air Temperature
   d. Mean 20cc Earth Temperature
   e. Mean 20cc Earth Temperature
   f. Mean Vapour pressure
   g. Growing degree days (GDD)
   h. Days of Snow
   i. Low Maximum Air Temperature
   j. Standard (std) Day mean Temperature
   k. Low Daily Mean Temperature
   l. High (hi) Daily Mean Temperature
   m. Mean 9 am Relative Humidity (RH)
   n. Mean 9 am Temperature
3. The most influencing weather variables (significant at *p-value*=0.05) selected from one way ANOVA tests are further analysed using rule and decision tree based data mining techniques (C5 decision tree of Clementaine) to establish the correlations between white and red original vintage ratings (2-7) and the selected significant climate variables.

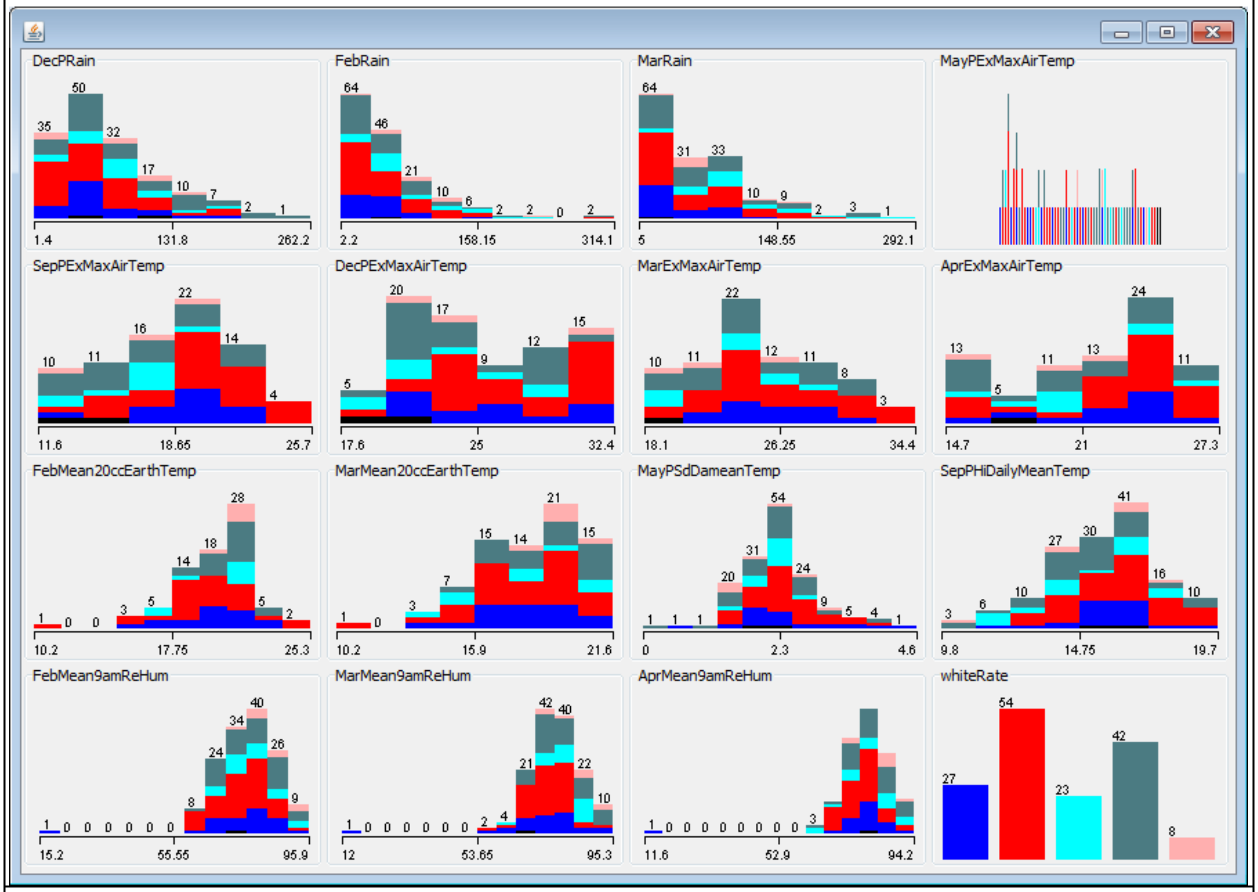
Despite the inconsistencies in the weather data set, rules created using this regional vintage quality and weather data show interesting patterns in the seasonal effects of weather on the quality of white and red vintages at the regional level across New Zealand and are discussed in the next section.

## 5. Results: New Zealand wine regional vintage quality and climate change

The vital factors relating to seasonal climate conditions that contribute to higher/lower vintage ratings for white and red wine styles at the regional scale in wine quality identified by ANOVA tests are listed Table 1 a-c. Table 1 a: consists of variables for white (left) and red wine (right), b: shows the data distribution of significant white vintage variables and c: shows the data distribution of significant red vintage variables. The C5 rules generated for white and red vintage regional ratings using the climate variables (presented in Table 1a) are listed in Tables 2 and 3 respectively.

The ANOVA results indicate a few variables i.e., December, February and March rainfall, as well as February and March mean 9 am relative humidity, as common deterministic variables for both, white and red regional vintage ratings in New Zealand. The possible interpretation for this could be as follows:

| wine | variable | F | sig | wine | variable | F | sig |
|---|---|---|---|---|---|---|---|
| white | Dec rainfall | 9.113 | 0.003 | red | Dec rainfall | 5.381 | 0.022 |
| | Feb rainfall | 4.061 | 0.046 | | Feb rainfall | 6.960 | 0.009 |
| | March rainfall | 11.906 | 0.001 | | March rainfall | 19.581 | 0 |
| | May extreme Max air T | 6.473 | 0.013 | | April rainfall | 6.127 | 0.014 |
| | Sep extreme Max air T | 12.233 | 0.001 | | July mean air T | 4.527 | 0.035 |
| | Dec extreme Max air T | 5.792 | 0.019 | | Aug low Max air T | 6.719 | 0.011 |
| | Mar extreme Max air T | 4.470 | 0.038 | | Feb mean 9am RH | 6.038 | 0.015 |
| | April extreme Max air T | 6.750 | 0.011 | | March mean 9am RH | 12.803 | --- |
| | Feb mean 20cc Earth T | 4.744 | 0.032 | | | | |
| | March mean 20cc Earth T | 4.020 | 0.048 | | | | |
| | May std daily mean T | 3.971 | 0.048 | | | | |
| | Sep high daily mean T | 7.938 | 0.006 | | | | |
| | Feb mean 9am RH | 4.965 | 0.027 | | | | |
| | March mean 9am RH | 13.710 | --- | | | | |
| | April mean 9am RH | 7.479 | 0.007 | | | | |




a: ANOVA results showing the monthly climate variables that affect the regional wine quality in NZ. Only the variables that have *P-value*<0.05 are listed and used in the subsequent artificial intelligent rule development tests using a C5 algorithm. T: Temperature Max: Maximum RH: Relative Humidity
b: Data distribution of monthly climate variables (based on ANOVA test results) that affect the regional white vintage quality in NZ. For each of the variables in Table 1 a (left), the distribution in terms of vintage rating value (7, 6, 5, 4, 3, as given by the histogram colours at the bottom right hand corner) against frequency (*y-axis*) and value (*x-axis*).

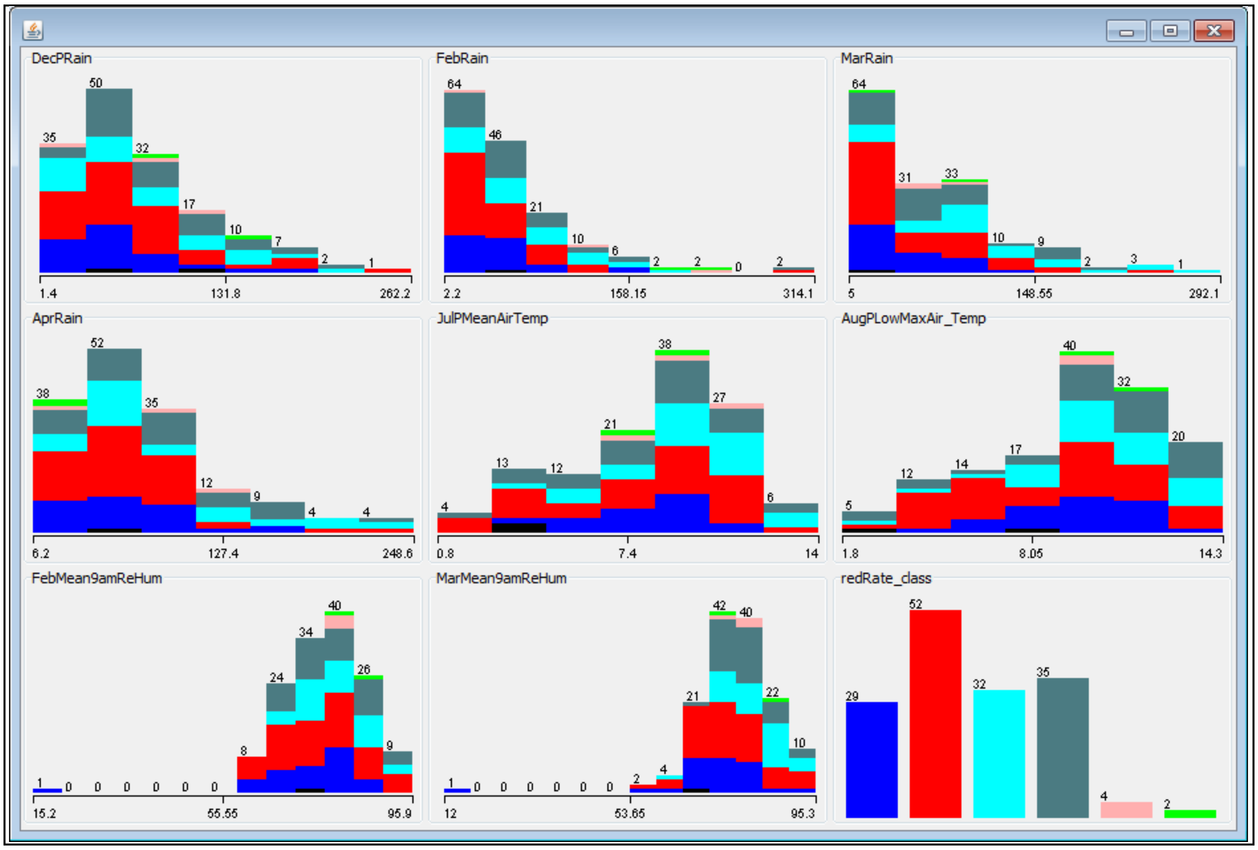



**Table 1.** c: Data distribution of monthly climate variables (based on ANOVA test results) that affect the regional red wine quality in NZ. For each of the variables in Table 1 a (right), the distribution in terms of wine rating value (7, 6, 5, 4, 3, 2) as given by the histogram colours at the bottom right hand corner) against frequency (*y-axis*) and value (*x-axis*).

1. Monthly rainfall totals in December, February and March: heavy rains in December affect the pollination in flowers and in turn reduce berry formation or fruitfulness meanwhile, increased rainfall in February and March affects the berry ripening process and reduce fruitfulness.
2. February and March monthly mean 9 am relative humidity: this is the berry ripening period in northern and southern regions in New Zealand. Higher relative humidity and rainfall increase the possibilities of increased fungal spread affecting the subsequent crop.

**Seasonal climate effects on white and red wine regional vintage ratings**

For **white** vintage ratings, February monthly rain (condition 1 in Table 2) seen as the major deterministic factor, i.e., increase in rainfall (>15.8 mm) when met with other conditions leads to higher vintage ratings (6.7) in all NZ wine regions. Meanwhile, March mean 9 am relative humidity (condition 1 in Table 3) is seen as the major deterministic factor for **red** vintage ratings for all NZ regions, however its effects are mixed, negative in the eastern and southern parts of the North Island (Gisborne (3) and Hawke's Bay (4)) and in some northern parts (Marlborough (5) and Nelson (6)) of the South Island except for Wairarapa (9) in southern North Island, and in rest of the New Zealand regions seems to be causing a positive effect on **red** vintage ratings.

## Seasonal climate effects on white wine regional vintage ratings

| region | rate | rule No | Condition 1 | Condtion 2 | Condition 3 | Condition 4 | | |
|---|---|---|---|---|---|---|---|---|
| | 6 | 1/10 | Feb rain <= 18.5 | | | | | |
| Auckland 1 | 4 | 1/7 | Feb rain > 15.8 | Feb mean 9am RH <= 85.5 | Sep hi dmean temp <= 15.2 | | | |
| | 5 | 1/11 | Feb rain > 15.8 | Feb mean 9am RH >85.5 | | | | |
| | 6 | 2/10 | Feb rain >15.8 | Feb mean 9am RH <= 85.5 | Sep hi dmean temp > 15.2 | Mar Ex max air temp <= 24.8 | | |
| | 7 | 1/6 | Feb rain >15.8 | Feb mean 9am RH <= 85.5 | Sep hi dmean temp > 15.2 | Mar Ex max air temp > 24.8 | | |
| Caterbury 2 | 4 | 2/7 | Feb rain > 15.9 | Sep hi dmean temp <= 14.2 | Sep Ex max air temp > 20.9 | | | |
| | 5 | 2/11 | Feb rain > 15.8 | Sep hi dmean temp <= 14.2 | Sep Ex max air temp <= 20.10 | | | |
| | 6 | 3/10 | Feb rain > 15.8 | Sep hi dmean temp > 14.2 | Mar mean 9am RH > 67.3 | | | |
| | 7 | 2/6 | Feb rain > 15.8 | Sep hi dmean temp > 14.2 | Mar mean 9am RH <= 67.3 | | | |
| Gisborne 3 | 4 | 3/7 | Feb rain > 15.8 | Mar mean 9am RH >76.9 | Feb rain > 37.6 | | | |
| | 5 | 3/11 | Feb rain > 15.8 | Mar mean 9am RH >76.10 | Feb rain <= 37.6 | | | |
| | 6 | 4/10 | Feb rain > 15.8 | Mar mean 9am RH <= 76.10 | Mar mean 9am RH > 73.2 | | | |
| | 7 | 3/6 | Feb rain > 15.8 | Mar mean 9am RH <= 76.10 | Mar mean 9am RH <= 73.2 | | | |
| Hawks Bay 4 | 4 | 4/7 | Feb rain > 15.8 | Apr mean 9am RH <= 77.3 | Sep hi dmean temp <= 17 | | | |
| | 5 | 4/11 | Feb rain > 15.8 | Apr mean 9am RH > 77.3 | Sep hi dmean temp > 15.1 | | | |
| | 6 | 5/10 | Feb rain > 15.8 | Apr mean 9am RH <= 77.3 | Sep hi dmean temp > 17 | | | |
| | 7 | 4/6 | Feb rain > 15.8 | Apr mean 9am RH > 77.3 | Sep hi dmean temp <= 15.1 | | | |
| Marlborough 5 | 3 | 1/3 | Feb rain > 15.8 | Apr ex max air temp <= 22.8 | | | | |
| | 5 | 5/11 | Feb rain > 15.8 | Apr Ex max air temp > 22.8 | Mar Ex max air temp <= 26. | Sep Ex max air temp > 15.8 | | |
| | 6 | 6/10 | Feb rain > 15.8 | Apr Ex max air temp > 22.8 | Mar Ex max air temp <= 26.7 | | | |
| | 7 | 5/6 | Feb rain > 15.8 | Apr Ex max air temp > 22.8 | Mar Ex max air temp > 26.7 | Sep Ex max air temp > 15.8 | | |
| Nelson 6 | 5 | 6/11 | Feb rain > 15.8 | Mar mean 20cc Earth temp <= 18.6 | | | | |
| | 6 | 7/10 | Feb rain > 15.8 | Mar mean 20cc Earth temp > 18.6 | | | | |
| Northland 7 | 3 | 2/3 | Feb rain > 15.8 | Mar mean 20cc Earth temp > 19 | Dec rain <= 123.6 | Mar rain > 46.6 | Maysd dmean temp <=1.4 | |
| | 3 | 3/3 | Feb rain > 15.8 | Mar mean 20cc Earth temp > 19 | Dec rain <= 123.6 | Mar rain > 46.6 | Maysd dmean temp > 1.4 | Dec rain > 79.4 |
| | 4 | 5/7 | Feb rain > 15.8 | Mar mean 20cc Earth temp > 19 | Dec rain < 123.6 | Mar rain > 46.6 | Maysd dmean temp > 1.4 | Dec rain <= 79.4 |
| | 5 | 7/11 | Feb rain > 15.8 | Mar mean 20cc Earth temp > 19 | Dec rain <= 123.6 | Mar rain <= 46.6 | | |
| | 5 | 8/11 | Feb rain > 15.8 | Mar mean 20cc Earth temp > 19 | Dec rain > 123.6 | | | |
| | 6 | 8/10 | Feb rain > 15.8 | Mar mean 20cc Earth temp <= 19.5 | | | | |
| Waikato 8 | 4 | 6/7 | Feb rain > 15.8 | Sep hi dmean temp > 15.3 | | | | |
| | 5 | 9/11 | Feb rain > 15.8 | Sep hi dmean temp <= 15.3 | | | | |
| Wairarapa 9 | 5 | 10/11 | Feb rain > 15.8 | Feb rain > 57.2 | Feb mean 9am RH <=83.4 | | | |
| | 6 | 9/10 | Feb rain > 15.8 | Feb mean 9 am RH > 83.4 | | | | |
| | 7 | 6/6 | Feb rain > 15.8 | Feb rain <= 57.2 | | | | |
| Otago 10 | 4 | 7/7 | Feb rain > 15.8 | Apr mean 9 am RH > 77 | | | | |
| | 5 | 11/11 | Feb rain > 15.8 | Mar mean 9am RH <=77 | Apr Ex max air temp <= 16.3 | | | |
| | 6 | 10/10 | Feb rain > 15.8 | Mar mean 9am RH <=77 | Apr Ex max air temp > 16.3 | | | |

**Figure 2.** Climate variables determinant (identified through ANOVA tests) for NZ **white** grape wine, regional vintage rating and rules created using a C5 algorithm.
rain: rainfall, RH: relative humidity, hi: high, temp: temperature, Ex: extreme, max: maximum, d: daily.

Based on Tables 1 and 2, September extreme maximum and daily high temperatures (see conditions 2 and 3 in Table 2) and are found to be the significant determinants of white vintage regional rating in New Zealand, the reason for this could be that this is the month in which buds burst occurs in southern hemisphere, an important phenological event of grapevine growth cycle. During this time buds begin to swell and burst into leaves and inflorescence, finally forming a shoot. For Auckland, Waikato, Hawke's Bay (of North Island) and Canterbury (from upper South Island) September high temperature seems to be one of the deterministic factors in the regional vintage rating of white wine styles. For example, for Canterbury (2), along with February total rainfall > 15.8 and <=18.5 mm, September high daily temperature >14.2 °C and March mean 9 am relative humidity <= 67.3 produced the highest ratings of 4-7. For the same region, September high daily temperature <14.2°C brought the rating down to 5/4, the monthly extreme maximum temperature >20.9 °C led to 4 and greater i.e., <=20.10 °C to 5. Otago region does not seem to be affected by the September extreme temperature. For the other regions data was not included in the analysis due to unavailability.

In Table 2, monthly rainfall totals in March and December (conditions 2, 3 and 4) are also seen as major deterministic factors for white wine regional vintage rating for Northland (7), Gisborne (3) and Wairarapa (9) regions, all of them from northern New Zealand, interestingly, it is more so in the extreme north, regions that are more exposed to the oceans.

In the Marlborough region in addition to the February monthly rain (condition 1 in Table 2), monthly extreme maximum temperatures of April > 22.8 °C, March >26.7 °C and September 15.8 °C (conditions 2-4 in Table 2) are seem to be the deterministic factors in the vintage ratings of white wine styles, higher temperatures in all three months experienced in this region seem to be producing the highest rating of 4-7.

**Seasonal climate effects on red wine regional vintage rating**

Based on Table 3, August low maximum (max) air temperate (condition 3 Table 3) in Auckland (1) and Hawke's Bay (4) seem to be the final deterministic factor, low temperatures leading to higher (6 and 7 respectively) confirm the fact that low temperatures during dormancy is vital for ultimate quality of the berry in the following season (growth cycle). This indicates that increase in August low maximum temperatures in these regions could lead to decrease in red vintage ratings.

Except for Auckland, all the other regions have either or all of December, February and March monthly total rainfall as deterministic factors (conditions 2-4 of Table 3). Interestingly, for all three months, higher rainfall leads to lower ratings, this implies that in general, any increase in rainfall could affect the red vintage rating in New Zealand. Again, in Canterbury (2), Hawk's Bay (4) and Wairarapa (9) (of the North Island) lesser monthly rainfall in December (condition 2 in Table 3) seems to lead to higher ratings, December being the time during which pollination takes place and heavy rains could severely hider the opening of flowers (cap fall) affecting pollination and in turn fruitfulness for the season.

The major deterministic factor for red wine regional rating is March mean 9 am relative humidity (RH) (condition 1 of Table 3). This is the time berry ripening occurs and higher percentages of relative humidity could create favourable conditions for fungal infections that severely hamper the crop unless fungicides are sprayed to avoid extensive damage to berry bunches and leaves. Therefore, in general during this period, low moisture and relative humidity conditions are preferred and this is evident from this rule. But based on condition 1-4 of Table 3, moderately high March relative humidity (72.8 - 80.6 %) has increased the red vintage ratings in Auckland (1) Canterbury (2), Northland (7) and Waikato (8). However, in Wairarapa (9) > 86.9 % along with December rain <=102.6 mm has led to the highest rating 7. On the hand, in Otago (10) increase in March relative humidity and February rainfall (>57.3 mm) are seen to be contributing to the higher rating of 5-6. The reason for this could be that the Otago (10) wine region is in the most southern part of New Zealand, where grape ripening is delayed with late harvest in June hence the region is benefited by any increase in both of these conditions.

| region | rate | rule No | Condition 1 | Condtion 2 | Condition 3 | Condition 4 |
|---|---|---|---|---|---|---|
| Auckland 1 | 5 | 2/11 | Mar mean 9am RH > 72.8 | Mar mean 9am RH <= 81.9 | Aug low max air temp > 12.7 | |
| | 5 | 3/11 | Mar mean 9am RH > 72.8 | Mar mean 9am RH > 81.9 | | |
| | 6 | 4/12 | Mar mean 9am RH > 72.8 | Mar mean 9am RH <= 81.9 | Aug low max air temp <= 12.7 | Mar mean 9am RH > 80.6 |
| | 7 | 1/9 | Mar mean 9am RH <= 72.8 | | | |
| | 7 | 7/9 | Mar mean 9am RH > 72.8 | Mar mean 9am RH <= 81.9 | Aug low max air temp <= 12.7 | Mar mean 9am RH <= 80.6 |
| Caterbury 2 | 4 | 1/7 | Mar mean 9am RH <= 72.8 | FebRain > 62 | | |
| | 4 | 2/7 | Mar mean 9am RH > 72.8 | DecPRain > 83.6 | | |
| | 6 | 1/12 | Mar mean 9am RH <= 72.8 | FebRain <= 62 | FebRain <= 40.8 | |
| | 6 | 5/12 | Mar mean 9am RH > 72.8 | DecPRain <= 83.6 | FebRain > 18.6 | |
| | 7 | 2/9 | Mar mean 9am RH <= 72.8 | FebRain <= 62 | FebRain > 40.8 | |
| | 7 | 8/9 | Mar mean 9am RH > 72.8 | DecPRain <= 83.6 | FebRain <= 18.6 | |
| Gisborne 3 | 4 | 3/7 | Mar mean 9am RH > 72.8 | JulPMeanAirTemp > 8.9 | DecPRain <= 54.8 | |
| | 5 | 4/11 | Mar mean 9am RH > 72.8 | JulPMeanAirTemp > 8.9 | DecPRain > 54.8 | |
| | 6 | 6/12 | Mar mean 9am RH > 72.8 | JulPMeanAirTemp <= 8.9 | | |
| | 7 | 3/9 | Mar mean 9am RH <= 72.8 | | | |
| Hawks Bay 4 | 4 | 4/7 | Mar mean 9am RH > 72.8 | FebRain > 47.8 | | |
| | 5 | 5/11 | Mar mean 9am RH > 72.8 | FebRain <= 47.8 | Aug low max air temp > 10.1 | |
| | 6 | 2/12 | Mar mean 9am RH <= 72.8 | DecPRain > 38.4 | | |
| | 6 | 7/12 | Mar mean 9am RH > 72.8 | FebRain <= 47.8 | Aug low max air temp <= 10.1 | |
| | 7 | 4/9 | Mar mean 9am RH <= 72.8 | DecPRain <= 38.4 | | |
| Marlborough 5 | 4 | 5/7 | Mar mean 9am RH > 72.8 | MarRain > 68 | | |
| | 5 | 6/11 | Mar mean 9am RH > 72.8 | MarRain <= 68 | | |
| | 7 | 5/9 | Mar mean 9am RH <= 72.8 | | | |
| Nelson 6 | 4 | 6/7 | Mar mean 9am RH > 72.8 | MarRain > 113 | | |
| | 5 | 7/11 | Mar mean 9am RH > 72.8 | Aug low max air temp > 10 | | |
| | 6 | 8/12 | Mar mean 9am RH > 72.8 | Aug low max air temp <= 10 | | |
| | 7 | 6/9 | Mar mean 9am RH <= 72.8 | | | |
| Northland 7 | 4 | 7/7 | Mar mean 9am RH > 72.8 | MarRain > 33.7 | Mar mean 9am RH <= 88.1 | MarRain > 62.2 |
| | 5 | 8/11 | Mar mean 9am RH > 72.8 | MarRain <= 113 | MarRain > 84.8 | |
| | 6 | 9/12 | Mar mean 9am RH > 72.8 | MarRain <= 113 | MarRain <= 84.8 | |
| Waikato 8 | 2 | 1/1 | Mar mean 9am RH > 72.8 | MarRain <= 33.7 | | |
| | 3 | 1/2 | Mar mean 9am RH <= 72.8 | | | |
| | 5 | 9/11 | Mar mean 9am RH > 72.8 | MarRain > 33.7 | Mar mean 9am RH <= 88.1 | MarRain <= 62.2 |
| Wairarapa 9 | 3 | 2/2 | Mar mean 9am RH > 72.8 | DecPRain > 102.6 | | |
| | 5 | 10/11 | Mar mean 9am RH > 72.8 | DecPRain <= 102.6 | Mar mean 9am RH <= 80 | |
| | 6 | 10/12 | Mar mean 9am RH > 72.8 | MarRain > 33.7 | Mar mean 9am RH > 88.1 | |
| | 6 | 11/12 | Mar mean 9am RH > 72.8 | DecPRain <= 102.6 | Mar mean 9am RH > 80 | Mar mean 9am RH <= 86.9 |
| | 7 | 9/9 | Mar mean 9am RH > 72.8 | DecPRain <= 102.6 | Mar mean 9am RH > 80 | Mar mean 9am RH > 86.9 |
| Otago 10 | 5 | 1/11 | Mar mean 9am RH <= 72.8 | FebRain > 36.6 | | |
| | 5 | 11/11 | Mar mean 9am RH > 72.8 | FebRain <= 57.2 | | |
| | 6 | 3/12 | Mar mean 9am RH <= 72.8 | FebRain <= 36.6 | | |
| | 6 | 12/12 | Mar mean 9am RH > 72.8 | FebRain > 57.2 | | |

**Table 2.** Climate variables found as significant deterministic factors (through ANOVA tests) for NZ **red** grape wine, regional rating and rules created using a C5 algorithm.

# 6. Conclusion

A few critical studies on recent climate change effects on the phenological development and ecological dynamics of some natural habitats described in the introduction, reported on the current and potential detrimental outcome on the biodiversity of the particular habitats. On the extreme, the effects are witnessed to be causing "*temporal mismatch in interacting species*" that have co-evolved over millions of years. As far as viticulture and wineries are concerned even though "*regime shifts*" in base viticulture climate have not been reported yet, signs are that this could happen in two popular wine regions in the very near future and they are: 1) within the next two decades in certain major wine producing regions of Australia, and 2) with an over 1 $^{o}$C increase in average temperature in some of the world famous *Mediterranean* wine regions.

The studies from literature relating to climate change effects on viticulture, wine production and quality discussed in section 2 have used conventional statistical methods and data spanning at least three decades. However, in *New* wine countries consistent data is not available for such time span hence it is not possible to study the climate change effects on viticulture and wine production, especially using conventional methodologies. In addition, New Zealand's wine regions have never been mapped for grape wine growing/ zoning/ marketing purposes. In this context, the paper presented an approach using statistical (ANOVA) and data mining (rule and tree based), with results interpreted in a geographical context. With this approach, it is possible to establish the key climate variables and the conditions that are vital to successful grapevine growing and the production of premium quality wines across the New Zealand at a regional scale.

The research discussed in the paper showed how disparate multi-sourced data could be transformed into useful knowledge with a GIS approach. The research results showed how inconsistent the climate change effects have been in the past within New Zealand and also gave some insight into potential future climate effects on both red and white vintage ratings in the country's major wine regions that have become world famous for their premium fine wine labels produced with some unique flavours.

The daily extreme temperatures (August low high, September daily high) and monthly rainfall effects on the regional vintage ratings of **white** and **red** wines produced from the north and south islands of the country clearly showed the varying climate effects across the country. In the extreme north and south increase in temperatures seems to influence the regional vintage ratings favourably in **white** wine varieties but not in the **red** vintages. The only temperature variable that showed significant impact on red vintages is August low maximum temperature in Auckland (1) and Hawke's Bay (4 in the North Island possibly affecting grapevine dormancy. Increased February rainfall (>15.8 mm) in all NZ regions along with other conditions (mainly relating to December and March rain and September high daily mean temperature) seems to lead to increase in **white** wine vintage ratings across the county.

Interestingly, monthly rainfall and relative humidity of certain months have been the significant climate variables for **red** vintages in New Zealand's wine regions. Increased rainfall in December, February and March seems to affect the regional vintage ratings of **red** wine except for Otago where >57.2 mm February rainfall combined with increased March mean 9 am relative humidity > 72.8 %, is seen to be leading to an increase in **red** vintage rating i.e., 6. The reason for Otago's positive response i.e., leading to a higher rating, to increases in these conditions could be that it is in the most southern part of New Zealand where grape ripening is delayed with late harvest is June. But March relative humidity in general seems to have negative effects on red vintages produced from the wine regions in eastern and southern parts of the North Island as well as in upper South island.

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