The effect of weather on critic ratings and auction prices for Stellenbosch Bordeaux blends from 2001-2021.

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Abstract

Growing season conditions are crucial in determining the quality of grapes in a vineyard. Identifying the climate variables with the greatest effect is therefore of interest to viticulturists and winemakers. Continued warming is evident for Stellenbosch since 2001, especially the last ten years. This study models the effect of temperature and rainfall variables on wine quality, represented by wine ratings and auction prices for Stellenbosch Bordeaux-style red wines. Findings indicate that, in terms of the relationship between weather and wine quality, Stellenbosch aligns more closely with Australia than Bordeaux. Growing season temperatures and harvest rainfall play a significant role in determining the outcome of a vintage. An optimal growing season temperature is estimated at 20.5°C. A climate-based vintage heuristic suggests that vintages with growing season temperatures near 20.5°C and January-February rainfall below 60mm are more likely to be exceptional. The heuristic suggests that the 2008 and 2011 vintages are undervalued, and a great 2024 vintage is to be expected. Rating inflation is evident for the portfolio of wines assessed. Similarly, inflation-adjusted auction prices for these wines have increased more than 5% annually. This price growth represents real value appreciation, suggesting that rating inflation may be attributed to objectively better wines. Proven adaptation strategies will be critical as warming and rainfall variability intensify. The increase in ratings and auction prices may already reflect successful farmer adaptation. While Stellenbosch winemakers have demonstrated resilience, increasing water scarcity may elevate the importance of winter rainfall effects, mirroring trends seen in Bordeaux.

Acknowledgments

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Finally, to my wife Jackie – without your unwavering support, encouragement, and motivation, none of this would have been possible.

Table of Contents

List of Acronyms

CoCT:	City of Cape Town
CWG:	Cape Winemaker's Guild
GSAT:	growing season average temperature
GSDT:	growing season diurnal temperature
ha:	hectares
HR:	harvest rainfall
IPCC:	Intergovernmental Panel on Climate Change
Mha:	million hectares
MFT:	mean February temperature
MJT:	mean January temperature
ML:	million litres
MLR:	multiple linear regression
SAWIS:	South African Wine Industry Information and Systems
WCWSS:	Western Cape Water Supply System
WO:	Wine of Origin
WR:	winter rainfall

Figures and Tables

List of Figures

List of Tables

1. Introduction

South Africa's winemaking history stretches back to the arrival of the Dutch settlers in 1652. They ordered vine cuttings from Germany and France, and on the 2nd of February 1659 Jan van Riebeeck famously journalled: "Today, praise be to God, wine was made for the first time from Cape grapes…" (Estreicher, 2014). South Africa is now the world's seventh largest wine producer making up 4% of global production (930Ml), and the sixth largest wine exporter by volume (275Ml). The value of South Africa's wine exports is comparatively modest, amounting to approximately £570 million, ranking 11th globally (OIV, 2023).

In South Africa almost all wine is produced from grapes grown in the Western Cape. The wine industry's role in the Western Cape is substantial, contributing approximately R51 billion to GDP and supporting 245,000 jobs across farming, manufacturing, retail and hospitality industries. Wine tourism also plays a major role in the Western Cape economy, with many tourists quoting wine tourism as a specific purpose of visiting (FTI, 2024). In 2023, 2350 South African primary grape producers farmed on 87,848 hectares (ha) across 11 wine regions. Approximately 65% of the crop share is white varieties, the most widely planted being Chenin Blanc (18%), Sauvignon Blanc (11%), Colombard (10%), Cabernet Sauvignon (10%), and Shiraz (10%) (SAWIS, 2023).

Studies have shown that the Western Cape has already been affected by systematic changes in weather (Bonnardot and Carey, 2008). Projections indicate continued warming of 1.5°C-3.0°C for the 2040-2060 period, with reductions in winter rainfall across the province (Midgley *et al.*, 2016; Carter, 2006). The Western Cape's agricultural, and by extension the local wine industry's success, is highly dependent on favorable growing conditions.

This study aims to model the effect of key climate variables, including temperature and rainfall on wine quality, using critic ratings and auction prices as dependent variables for Stellenbosch Bordeaux-style red wines. By analysing these relationships, it seeks to provide insights into how weather influences vintage quality in this region.

This paper is inspired by the work of Ashenfelter, Ashmore and Lalonde (1995) who developed the "Bordeaux equation". They concluded that the best vintages experience wet winters, warm growing seasons, and dry harvest months. Wine ratings for Stellenbosch - famously known for its Bordeaux blends and red noble varietal wines - are the focus of this paper. Stellenbosch is located in the South-West of the Western Cape (Figure 1.1 & Table 1.1). It has a temperate, Mediterranean-type climate with mild, wet winters and warm, dry summers (Schulze, 1972), closely aligning with Ashenfelter's criteria for great Bordeaux-varietal growing conditions.

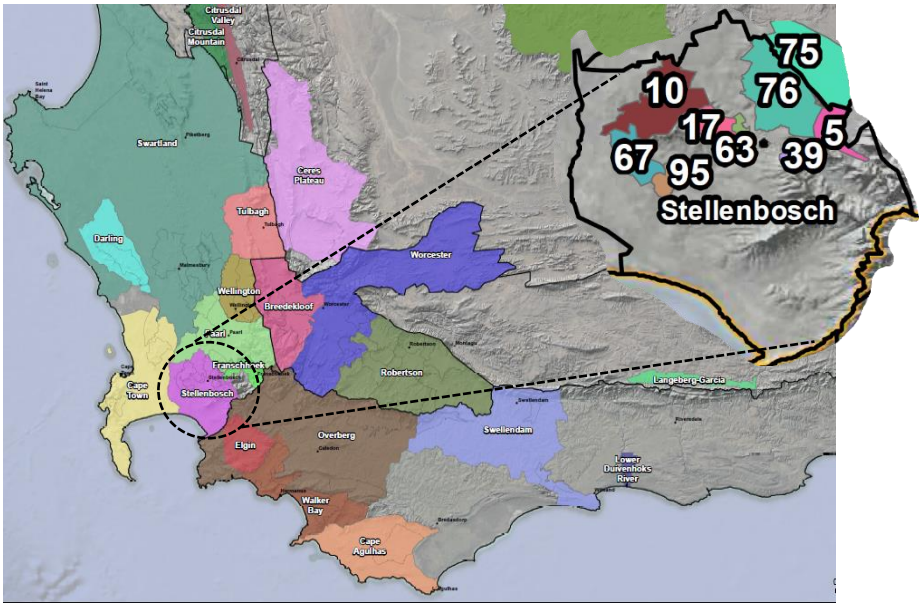
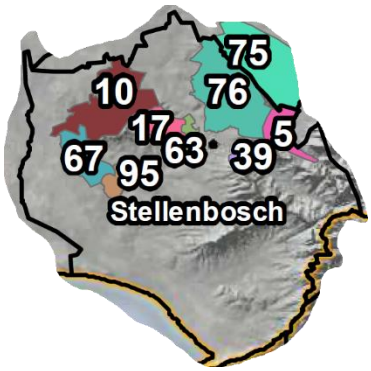


Figure 1.1: Wine of Origin Districts, Stellenbosch enlarged. (Source: SAWIS, 2024).

Table 1.1: Wine of Origin Wards within the Stellenbosch district (Source: SAWIS, 2024).

Ward Name
05 - Banghoek
10 - Bottelary
17 - Devon Valley
39 - Jonkershoek Valley
63 - Papegaaiberg
67 - Polkadraai Hills
76 - Simonsberg-Stell.
95 - Vlottenburg



The thesis begins with a literature review on climate change, weather's effect on vine phenology, and the impact of weather on wine quality. A global and local industry overview follows, providing context for the study. The methodology section details the research design, covering weather and ratings data, rating inflation, and auction data. The results section discusses weather's influence on wine quality ratings and auction prices. An optimal growing temperature is estimated, a climate-based vintage quality heuristic is proposed, and future vintage predictions are made. Finally, limitations are acknowledged, and conclusions are drawn, highlighting implications for the industry and areas for future research.

2. Literature Review

2.1 Climate Change

Climate change is a critical issue that could exacerbate the existing economic, political, and social challenges facing the industry, both domestically and abroad (Midgley *et al.*, 2016). Findings from the Intergovernmental Panel on Climate Change (IPCC) Assessment Report provide evidence of continued warming, changes in rainfall patterns, and increased frequency of extreme climatic events (IPCC, 2023).

The cause of climate change is largely due to the burning of fossil fuels and other activities that release gases such as carbon dioxide into the earth's atmosphere (IPCC, 2023). The collection of these toxic byproducts, referred to as Green House Gases (GHG), exerts a strong warming effect on the earth. Each of the least three decades have successively been warmer than any decade since 1850 (Figure 2.1). During the 30 years from 1983-2012, the Northern Hemisphere experienced its warmest 30-year period of the last 1400 years (IPCC, 2023).

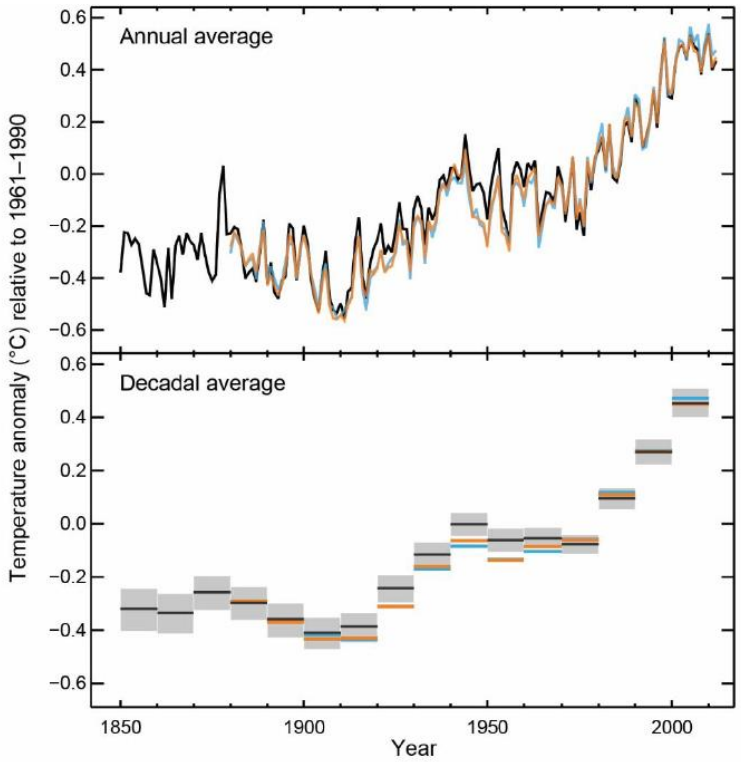


Figure 2.1: Observed globally averaged land and ocean surface temperature anomalies from 1850-2012. Different coloured lines represent datasets used. The top panel shows annual averages and bottom panel the decadal averages (Source: IPCC, 2023).

The latest version of the report confirms that global surface temperature has increased faster since 1970 than any other 50-year period over the last 2000 years. Estimated GHG emissions by 2030 will likely cause further warming of between 1.5-2°C by the end of the 21st century. Concerningly, the magnitude of climate change impacts is larger than previously estimated. In general, Africa can expect heightened risk of food security due to the reduced output from crops, livestock and fisheries (IPCC, 2023).

Studies have shown that the wine grape-growing epicentre of South Africa, the Western Cape, has already been affected by systematic changes in weather. According to Midgley *et al.* (2016), agriculture is driven by climate systems and sensitive to variability, with many commodities exposed to the effects of estimated climate change. Conservative projections predict warming of 1.5-3.0°C for the 2040-2060 period, accompanied by reductions in winter rainfall across the province (Midgley *et al.*, 2016). Projections for 2046-2065 over the Stellenbosch, Paarl and Franschhoek wine regions estimate a decreased winter rainfall of 20% (Carter, 2006). Bonnardot and Carey (2008) studied temperature changes in wine growing regions across the Western Cape from 1967 to 2006. They report an increase in maximum and minimum temperatures of 0.5-1.7°C depending on the region and period assessed.

The Western Cape's water supply is stored in 47 dams with a combined storage capacity of 1.9billion cubic meters (DWS, 2025), Figure 2.2 shows the storage levels for Cape Town's six dams since 2008. The three years spanning 2015-2017 saw significant decreases in dam levels due to a major drought which was in part averted due to the enforcement of water restrictions. From 2019 onward the Cape experienced a return to healthy damn levels. The 2023 season witnessed excessive winter rainfall, with the Wemmershoek Dam experiencing the highest June rainfall in 70 years, resulting in flooding across multiple sites which was followed by another major rainfall event in September (CoCT, 2024a).

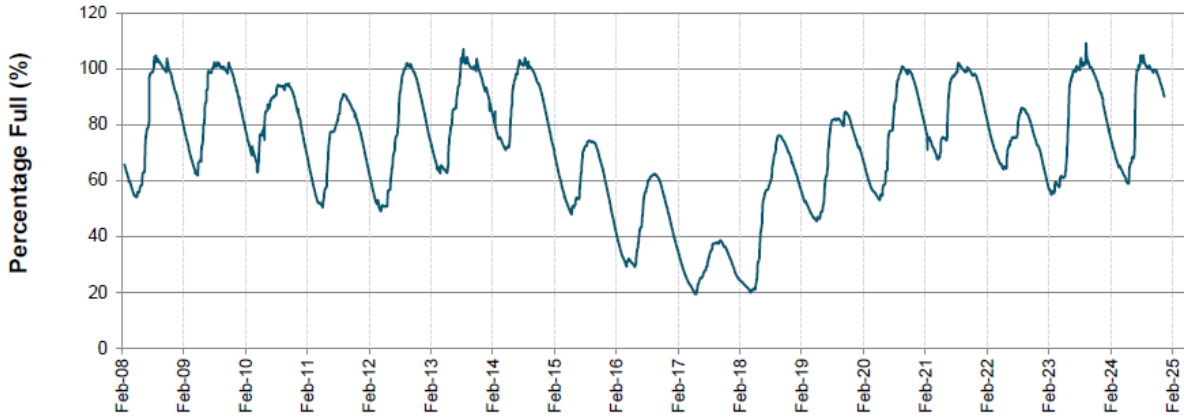


Figure 2.2: WCWSS Storage Record for the six major dams, 2008-2024 (Source: CoCT, 2024b).

Rain and temperature variables for the Western Cape are assessed by Mackellar *et al.* (2014). They find a positive trend in both mean annual maximum and minimum temperatures, increasing by approximately +0.2°C and +0.15°C per decade respectively, with high confidence. The number of rain days are decreasing at approximately 2 days per decade, with smaller reductions observed in summer (-0.5 days/decade) and autumn (-0.7 days/decade), with moderate confidence (Midgley *et al.*, 2016).

Midgley *et al.* (2016) highlight that water resources are already under significant stress, with a low level of assurance for agricultural use. Climate change is expected to intensify this pressure through rising demand, increased evapotranspiration, and volatile rainfall patterns.

2.2 Weather and Vine Phenology

Vines thrive in a variety of climates; however, major wine-growing regions are found between the 35-50th parallels in the Northern Hemisphere and 30-45th in the Southern Hemisphere. According to van Leeuwen and Darriet (2016:151), "it is virtually impossible to produce high-quality wines in tropical or subtropical regions". In comparison to other environmental factors, climate has the greatest impact on vine development and fruit composition. Varying annual climatic conditions directly affect yields and quality, subsequently inducing the "vintage effect" (van Leeuwen *et al.*, 2004). The concept of *terroir* is closely linked to weather's effect on vine phenology in a vineyard. Terroir refers to the integration of topography, geology, soil, and climate which comprises the vine's natural environment and influences the sensory attributes and typicity of the resulting wine (Gladstones, 2011).

Changes in climate affect the prices and quantities of wine produced in a vineyard, directly affecting revenues. Studies suggest that a vineyard's productivity and suitability of grape variety planted will change during a vine's lifetime, making short-term losses unavoidable (Gladstones, 1992). Unlike most agricultural products, fine wine can be stored for decades and often increases in real value with age. This durability has made it a sought-after alternative asset for portfolio diversification (Fogarty, 2010).

Grapevines have a distinct annual growth cycle known as the phenological stages. The first stage of the season is bud break, followed by bloom, berry growth and colouring, maturation, leaf fall, and then finally dormancy before the start of the next cycle (Gladstones, 2011). Appendix N contains a summary of grapevine growth stages. The timing of these stages is driven by growing season temperatures and varies annually. The relationship between stages of growth and temperature is so strong that vine phenology can be predicted based on temperature alone (Parker *et al.*, 2011).

The period of changing berry colour and ripening is referred to as veraison. During this stage, temperature affects the maturation of the berry, specifically its sugar, acidity, colour and flavour profile (Amerine and Winkler, 1944). Warmer growing season temperatures are associated with increased sugar accumulation and reduced acidity (Coombe, 1987). Extreme maximums in summer can cause heat damage, limiting photosynthesis, growth, ripening, and can lead to sunburn.

The regions of the world that produce high-quality wine rely on favourable growing season temperatures to produce a top vintage. Warmer vintages produce better wines in cooler regions like Bordeaux and the Rhine Valley (Ashenfelter, 2008), while warmer regions like Australia generally benefit from a cooler growing season (Byron and Ashenfelter, 1995).

Duchene and Schneider (2005) analysed meteorological and phenological data for the French region of Alsace from 1972-2003. Mean annual maximum and minimum temperatures during the ripening phase increased by 0.17°C and 0.13°C respectively. Additionally, they found that the period between budburst and harvest has been compressed and occurs earlier. They add that ripening is taking place under warmer conditions, and the risks associated with hot and dry summers will likely increase (Duchene and Schneider, 2005). Similar findings are reported by van Leeuwen and Darriet (2016) who state that harvest dates post-1980 have been consistently earlier in the Rhone Valley and Bordeaux due to increased temperatures (Figure 2.3).

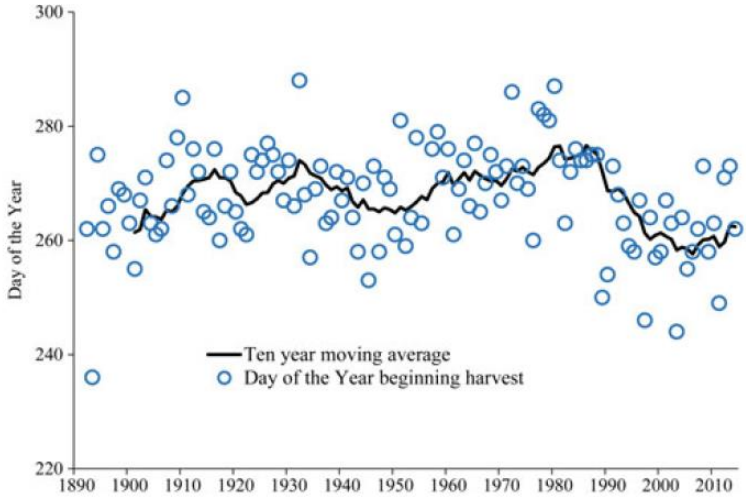


Figure 2.3: Harvest dates for an estate in Bordeaux from 1890 to 2015 (Source: van Leeuwen and Darriet, 2016).

Carey *et al.* (2008) found that in Stellenbosch, the phenology, growth, yield, berry composition, and wine-related characteristics of Cabernet Sauvignon are influenced by climate, soil properties, and topographical site characteristics.

2.3 Weather and Wine Quality

Ashenfelter, Ashmore and Lalonde (1995) famously developed the "Bordeaux Equation" that established the relationship between auction prices and climate in the famous French region for the period 1952-1980. A log-linear relationship exists between auction prices, the weather variables, and the age of the bottle at auction. The age of vintage had a positive effect, as expected, older bottles of wine are more matured, scarce, and garner higher prices. The growing season average temperature (GSAT) and winter rainfall had a positive effect, while rainfall in August – an important month during the harvest, had a negative effect. Their model explained 83% of the variation in Bordeaux auction prices.

Webb, Whetton and Barlow (2008) analysed 14 wine grape varieties across Australia and established a model using a single independent variable, Mean January Temperature (MJT) developed by Smart and Dry (1980), and its effect on wine quality, represented by price per tonne of grapes ($AUS.t^{-1}). They established that Cabernet Sauvignon has a quadratic relationship with quality, meaning that beyond a certain point, heat in the growing season becomes detrimental. The model explains 70% of the variance in wine price per tonne, and they estimate an optimum growing season temperature of 18.5°C for Cabernet Sauvignon across the Australian wine-growing regions.

In their analysis of the effect of temperature on auction prices of the iconic Australian Penfold's Grand Hermitage, Byron and Ashenfelter (1995) conclude that the Shiraz blend's auction price also has a quadratic relationship with GSAT. They develop a composite equation including variables accounting for the age of the wine, harvest rainfall, GSAT, GSAT^2, and growing season diurnal temperature (GSDT) which explains 82% of the variation in auction prices of a vintage. They conclude that the role of weather in determining the quality and price of a Penfold's Grange is less significant that in Bordeaux. A major distinction between the regions is that no winter rainfall effect is discovered for Australia.

In an analysis of weather's effect on wine quality and prices in Australia, Oczkowski (2016) finds that the best model specification for both Cabernet Sauvignon and Merlot include harvest rainfall, GSAT, GSAT^2, and the signs of the coefficients are as expected. Harvest rainfall negatively effects wine quality, and beyond a certain point warming becomes detrimental. The quadratic specification allows them to

find optimal growing season temperatures for Cabernet Sauvignon and Merlot of 18.6°C and 17.5°C. The models explain 45% and 60% of the variation in price for Cabernet Sauvignon and Merlot respectively.

In their comparison of American and Burgundian Pinot Noir, Haeger and Storchmann (2006) analysed the effect of climate, critics' scores, and winemaker-related variables on price. Rainfall in Burgundy matters but is not significant in the USA. While the GSAT relationship in Burgundy is linear, American Pinot Noir exhibits a quadratic relationship. Warmer growing seasons are beneficial for Burgundy, but the opposite is true for their American counterparts. Regions like California and Oregon are at or near the optimum GSAT for this cultivar, and further warming will have a negative effect on retail prices. In general, the effect of weather in American Pinot Noir regions is less than in Europe. The quadratic GSAT specification accounts for 52% of the variation in wine prices in the US, compared to a linear specification in Burgundy with 61% (Ashenfelter, 2017).

Another study in Burgundy compared climate variables and the associated vintage ratings from 12 professional critic sources for the period 1961-2015. The most important factor distinguishing the top 10 vintages from the bottom 10 was the presence of high temperatures in the growing season. The bottom ranked vintages all experienced cool and wet conditions during the growing season (Davis *et al.*, 2019). Using a discriminant function model approach, a line of separation is found that accurately yields the correct vintage classification based on two variables, rainfall during veraison and maximum temperature during the growing season. A similar heuristic is developed by Ashenfelter (2008) which entails plotting above and below average vintages on a graph of harvest rainfall and growing season temperatures. Above average vintages cluster in the quadrant which maximizes temperatures and minimizes rainfall.

Ramirez (2008) used 6000 observations of Cabernet Sauvignon wines rated by Wine Spectator from 1970 to 2004 in the Napa Valley region of California. Their findings indicate a linear relationship exists between weather and quality ratings. Although temperature and precipitation variables affect ratings, the temperature coefficients were not as expected, and the overall fit of the regression was relatively weak. The log-linear specification for prices however was clearly superior with an adjusted R-squared of 0.92, compared to 0.28 for critic ratings. They concluded that cool, wet winters followed by dry and warm growing seasons result in higher wine prices. In Napa Valley, weather does matter, however the effect on wine prices is much greater than wine ratings (Ramirez, 2008).

Kopsacheilis *et al.* (2024) investigated how ratings from a crowdsourced platform, Vivino, and professional critics respond to weather conditions. Taking inspiration from Ashenfelter's "Bordeaux Equation" (2008), the same linear model specification finds that temperature, precipitation, and trend variables account for 40% of the variation in amateur critics, and 63% of the variation in professional critic ratings. Based on the magnitude of the coefficients, expert ratings are more responsive to the effect of weather on wine quality.

Jones *et al.* (2005) studied the effect of temperature on the wine quality ratings across 23 regions during the period 1963-2000. They found that from 1950-1999, GSAT in the world's high quality wine regions increased by 1.26°C. Secondly, they concluded that 10-60% of the variation in vintage quality ratings were explained by GSAT alone, with the greatest effects visible in the cool climate regions. Finally, based on the quadratic modelling approach, the optimum GSAT for each of twelve regions was estimated (Table 2.1). By 1999, five of the 12 regions had a GSAT at or beyond the estimated optimum value. Selected regions are depicted in Figure 2.4.

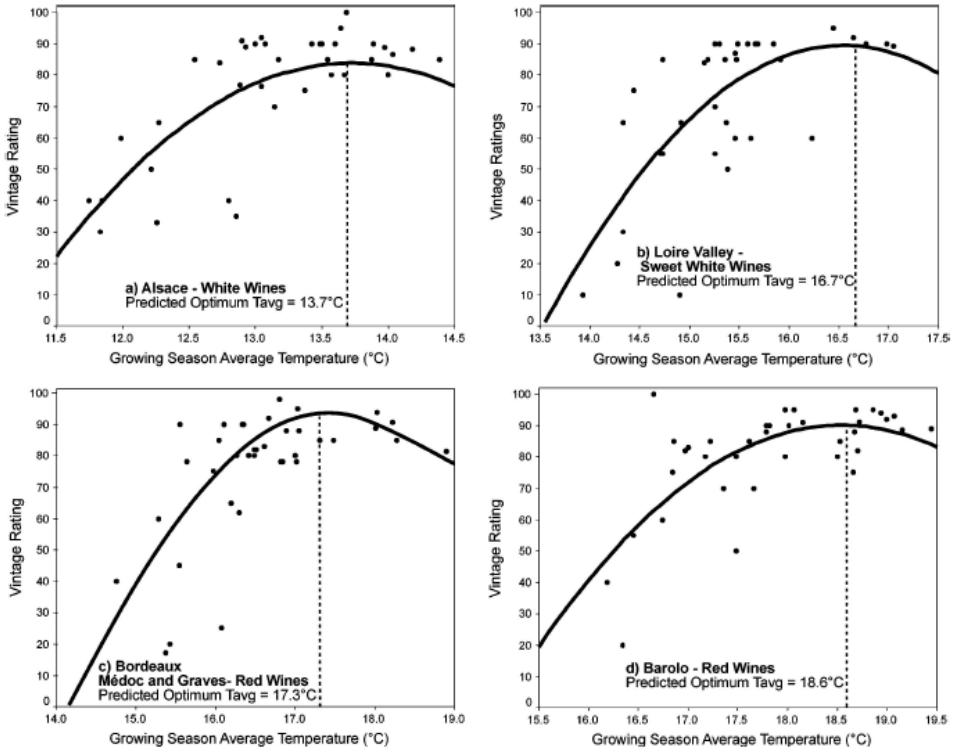


Figure 2.4: Predicted optimum GSAT for selected regions with a quadratic GSAT specification. Selected regions: Alsace, Loire Valley, Bordeaux, Barolo. The dashed line represents the estimated optimum per region (Source: Jones *et al.*, 2005).

According to projections from the HadCM3 climate model, by 2049 each of the 12 regions identified would be 0.11°C - 1.93°C beyond their estimated optimum GSAT values, at an average of 0.92°C (Table 2.1). The "Excess °C" column refers to the magnitude of warming by 2049 beyond the estimated optimal growing season temperatures (Jones *et al.*, 2005).

Table 2.1: Actual GSAT, estimated optimal, and predicted GSAT for wine regions (Adapted from Jones *et al.*, 2005).

Region	1950-1989[a]	1990-1999[a]	GSAT Opt.	1990-1999[b]	2000-2049[c]	Excess °C
Alsace W	12.9	13.8	13.7	0.1	0.94	1.04
Mosel W	12.9	13.4	13.9	-0.5	0.93	0.43
Champagne	14.3	15.0	15.0	0.0	0.87	0.87
Rhine W	14.7	15.5	15.6	-0.1	0.93	0.83
Loire SW	15.2	15.8	16.6	-0.8	1.01	0.21
Loire R	15.2	15.8	16.7	-0.9	1.01	0.11
Bordeaux[1]	16.2	17.5	17.3	0.2	1.20	1.40
Bordeaux[2]	16.2	17.5	17.5	0.0	1.20	1.20
Rioja R	16.3	18.1	17.5	0.6	1.33	1.93
Barolo R	17.5	18.8	18.6	-0.2	1.41	1.21
S. Rhone R	18.1	18.8	18.9	-0.1	1.24	1.14
Barossa W	20.0	19.6	19.9	-0.3	0.95	0.65

a: GSAT in °C. b: Difference between GSAT from 1990-1999 and Estimated Optimum GSAT.
W: White wines. SW: Sweet white wines. R: Red wines. 1: Medoc and Graves. 2: St Emilion and Pomerol.

According to Jones *et al.* (2005), the warming projections are greater for the Northern Hemisphere (2.11°C) than the Southern Hemisphere (1.71°C). The average change in warming over the 50-year period is projected to be 2.04°C, the highest in Southern Portugal (2.85°C), and the lowest in South Africa (0.88°C). They conclude that warming in the late 20th Century was generally beneficial for high quality winemaking but warn that further warming could be detrimental for those regions (Jones *et al.*, 2005).

Ashenfelter and Storchmann (2016) combine the work by Amerine and Winkler (1944) and Jones *et al.* (2005) and present viable GSAT ranges for selected cultivars. Three of the five cultivars relevant to this paper, namely Cabernet Franc, Merlot and Malbec all possess a theoretical upper bound of 19°C. Cabernet Sauvignon is shown to be more heat tolerant with an upper optimal bound 1°C higher than the other Red Bordeaux varietals (20.1°C) (Figure 2.5). They conclude that rising growing season temperatures will be beneficial and detrimental to viticulture, generally resulting in winners located towards the poles, and losers towards the equator (Ashenfelter and Storchmann, 2016).

Farmers of the varietals on the left half of the x-axis, like Riesling and Pinot Noir, have ample varietal substitution in the face of a warming growing temperatures. However, if a farmer finds the prevailing conditions already too warm for Grenache or Zinfandel for example, their alternatives are greatly minimised without considerable adaptation strategies (Ashenfelter and Storchmann, 2016).

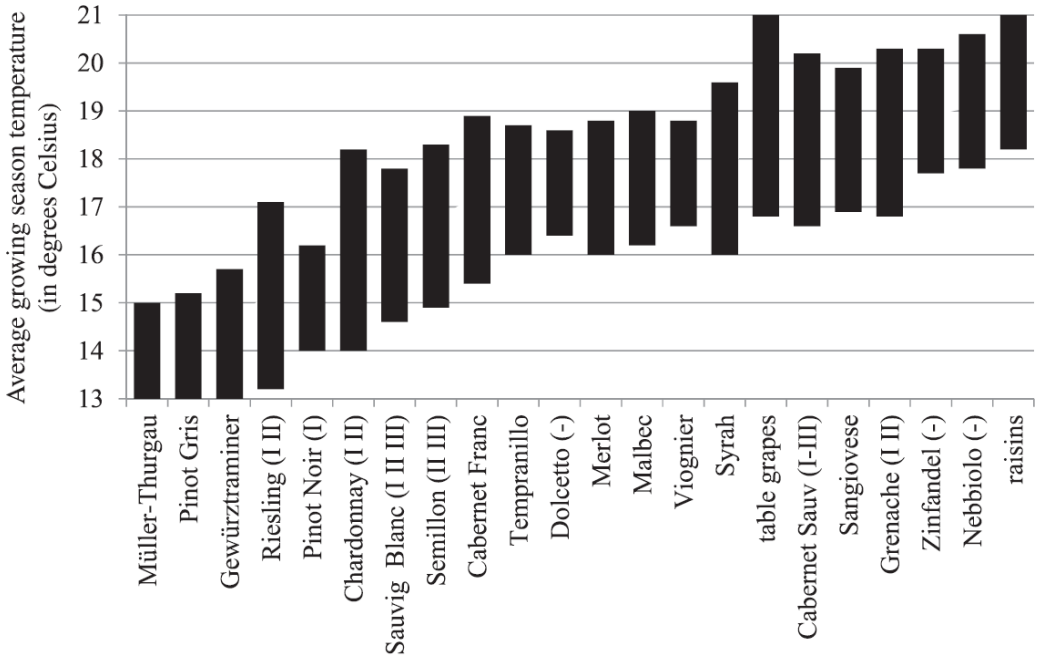


Figure 2.5: Estimated optimal GSAT for selected cultivars. Numbers in parentheses indicate Winkler regions for fully tested varieties (Petit Verdot not reported). (-) denotes partially tested varieties. The remaining varietals have not been tested (Source: Ashenfelter and Storchmann, 2016).

German wines are categorized by the degree of ripeness of the constituent grapes, measured in degree Oechsle, the natural sugar in the must upon harvest (Niklas, 2017). Greater sugar levels result in higher wine classifications. Niklas (2017) examined the effect of annual weather fluctuations on total wine production and the proportional change of quality categories in Germany. The study uses weather data from regional stations in each of the thirteen viticultural regions from 2003-2013. The number of soil-freezing days adversely affects wine production, while rising growing season temperatures have a significant positive impact on wine in higher-quality segments. The effect of climate change, specifically continued warming, will be highly beneficial to the German producers, as they will experience increased temperatures, drier growing seasons, and reduced soil-freezing days (Niklas, 2017). Over a longer period of study, Storchmann (2005) studied Riesling in the Rhine wine region of

Germany. Throughout a 300-year period, a 1°C increase in average growing season temperatures increases the odds of a top vintage from 20% to 50%, concluding that moderate global warming will improve the quality of Rhine wines.

Jones and Storchmann (2001) examine the wines of 21 Crus Classes chateaux in Bordeaux and find that warm and dry summers result in high sugar and low acid levels. Merlot-dominated wine is more climate sensitive than Cabernet Sauvignon, which agrees with the findings by Jones and Davis (2000). In vintages with excellent climate, Merlot-dominated wines are better quality than Cabernet Sauvignon; however, in average or marginal years the Merlot-dominated wines yield lower prices (Jones and Storchmann, 2001).

3. Industry Overview

The world's vineyard surface area has steadily decreased since 2003, contracting 8% from 7.8 to 7.2 million hectares (mha) in 2023. This marks three consecutive years in decline due to the uprooting of vines in both hemispheres (OIV, 2024).

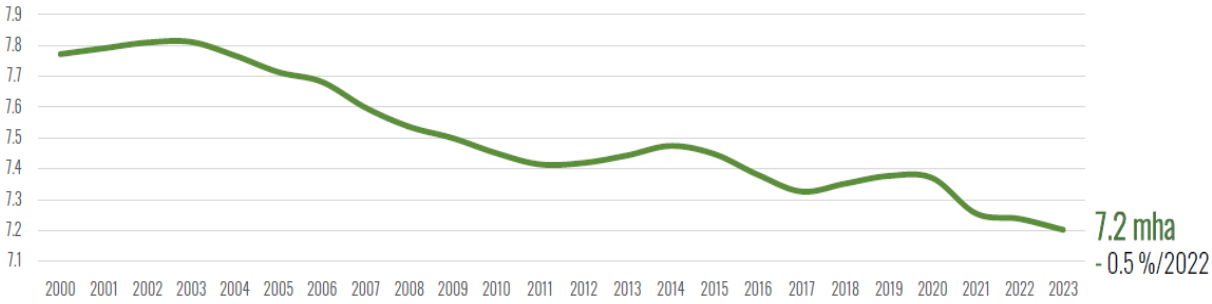


Figure 3.1: Worldwide vineyard surface area in mha, 2000-2023 (Source: OIV, 2024).

The removal of vineyards, extreme climatic conditions, and widespread fungal diseases have resulted in a meagre global wine production of 237 million hectolitres (mhl), a 10% year on year (YOY) decrease, down 20% from production highs in 2018, and the lowest output since 1961 (OIV, 2023). Fourteen of the top 21 wine-producing countries by volume experienced an annual contraction in production. The EU experienced an 11% drop to 145mhl, and the Southern Hemisphere contracted by 15% YOY to 47mhl. In 2023 the top five wine-consuming countries, namely USA, France, Italy, Germany, and the UK all decreased their annual consumption by 2-3%. In total, 15 of the top 20 major wine-consuming countries decreased their annual wine consumption in 2023 (OIV, 2023).

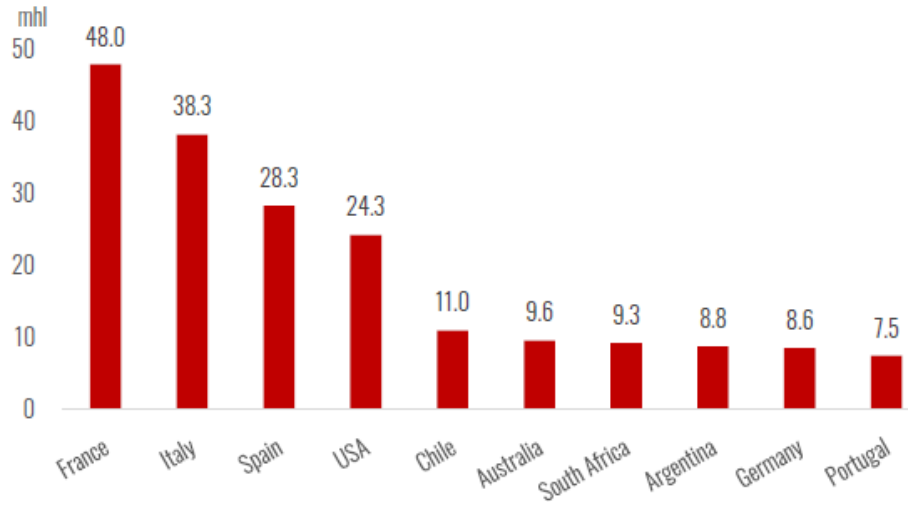


Figure 3.2: Top 10 wine-producing countries (Source: OIV, 2024).

In 2023, 2350 South African primary grape producers farmed on 87,848 hectares across 11 wine regions. Approximately 65% of the crop share is white varieties, the most widely planted being Chenin Blanc (18%), Sauvignon Blanc (11%), Colombard (10%), and Chardonnay (8%). The most planted red varieties are Cabernet Sauvignon (10%), Shiraz (10%), Pinotage (8%), and Merlot (6%) (SAWIS, 2024). The largest importers of South African bulk and packaged wine are the UK (80Ml), Germany (45Ml), and Canada (15Ml) (OIV, 2023).

The wine industry's role in the Western Cape is substantial, contributing approximately R51 billion rand to GDP and supporting 245,000 jobs across farming, manufacturing, retail and hospitality industries (FTI, 2024). Nationally, the wine industry contributes R57 Billion (1% of GDP), supporting 270,000 jobs (1.8% of employment). In 2022, the SA wine industry generated R19.3 billion in excise duties and VAT (1.2% of Tax Income), with the Western Cape accounting for R18 Billion (FTI, 2024).

Wine tourism plays a major role in the Western Cape economy, with many tourists quoting wine tourism as a specific purpose of visiting. A 2022 study concluded that wine tourism directly contributed R3.05 billion to the SA GDP, up from R2.4 billion in 2019 (I and M Futureneer, 2023).

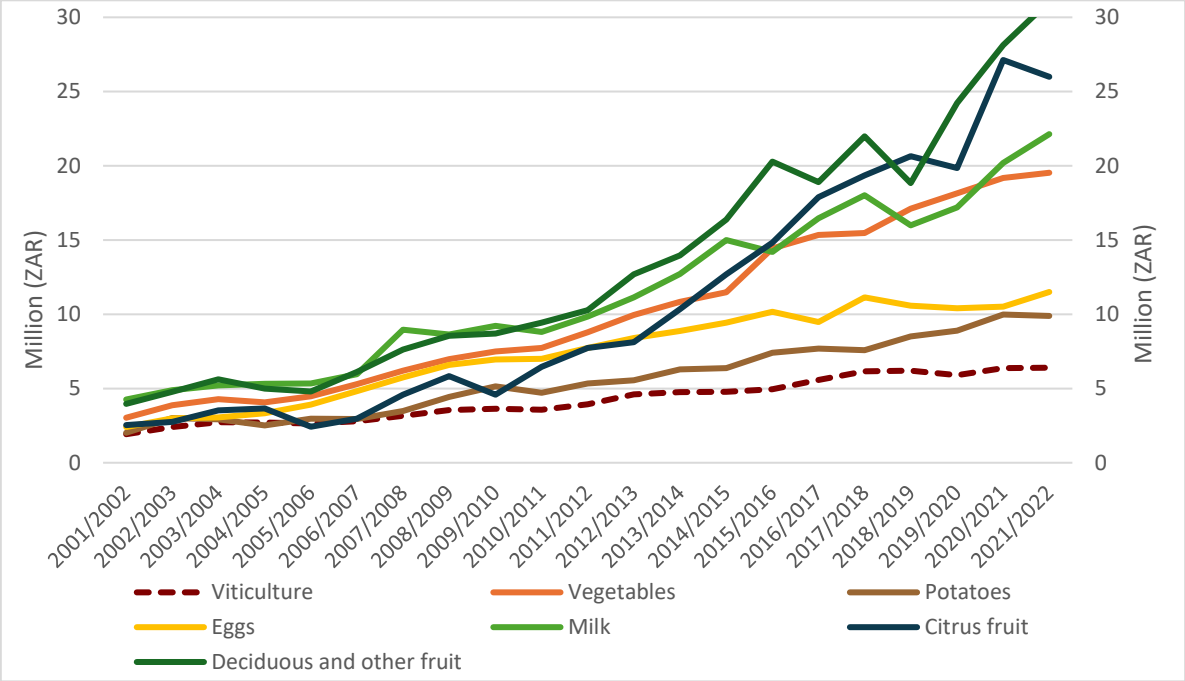


Figure 3.3: South African viticulture contribution relative to other major farming activities (Adapted from: Abstract of Agricultural Statistics, 2023).

The last decade has been a challenging one for the wine industry, with the Western Cape experiencing severe drought and water shortages peaking in 2017/2018. This was followed by the Covid-19 pandemic in which the government banned the local sales and export of wine and alcohol in general. Furthermore, many growers faced ongoing challenges due to loadshedding which greatly disrupted irrigation practices (Vinpro, 2023).

The industry's decline is evidenced in the comparison of viticulture's contribution to total agricultural production by value, and its share of total horticulture and total production. For the 2001-2022 period, it has experienced the slowest growth in contribution to agricultural production compared to other major farming practices (Figure 3.3). Viticulture as a proportion of horticultural and agricultural production halved from its peak in 2005 (Figure 3.4).

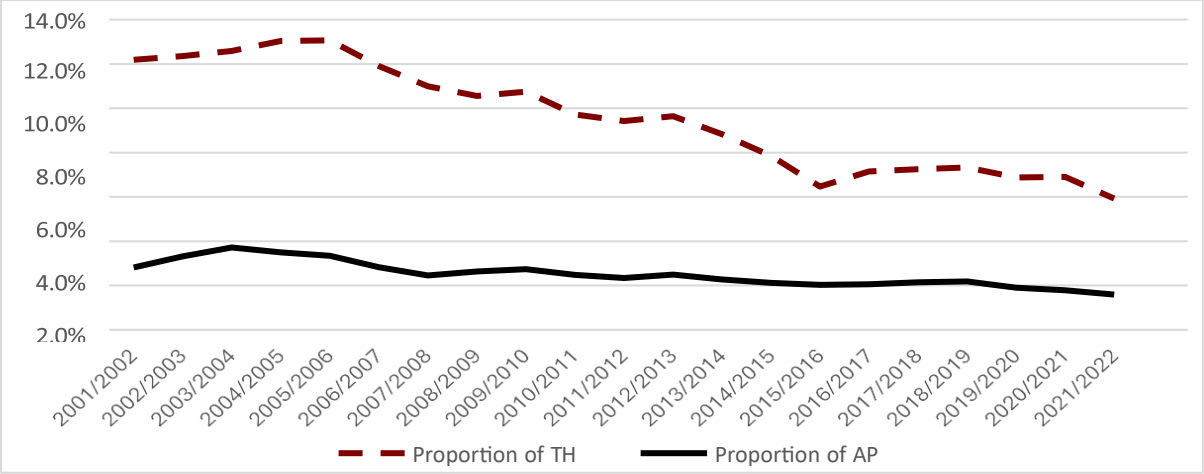


Figure 3.4: Viticulture as a proportion of Total Horticulture (TH) and Agricultural Production (AP) (Adapted from: Abstract of Agricultural Statistics, 2023).

Further evidence of the overwhelmingly challenging industry conditions is the declining trend of primary grape producers and vineyard hectares. Approximately a third of primary grape producers have exited the industry since 2013 (SAWIS, 2023). The varieties that have experienced the most significant uprooting since 1999 are those originally planted for brandy production, namely Chenin Blanc (-35%) and Colombard (-22%). A similar trend is observed for noble red grape varieties since 2009, with the area under Cabernet Sauvignon and Merlot decreasing by 27% and 21%, respectively (SAWIS, various years). Prolonged drought conditions (2016-2018) resulted in cost pressures and reduced profitability. Subsequently, farmers shifted to more profitable crops like citrus, plums, and blueberries (FTI, 2024).

The uprooting of vineyards in the Western Cape is outpacing replanting, with the total hectares under vineyards decreasing annually since 2006. Total vineyard area peaked at 102kha in 2006, reducing to 88kha in 2023, a 14% decrease (Figure 3.5). This is twice the decline of global vineyard area which contracted by 6.5% over the same period (OIV, 2024). Table 3.1 is adapted from Vink *et al.* (2018) and tracks important measures since 1995.

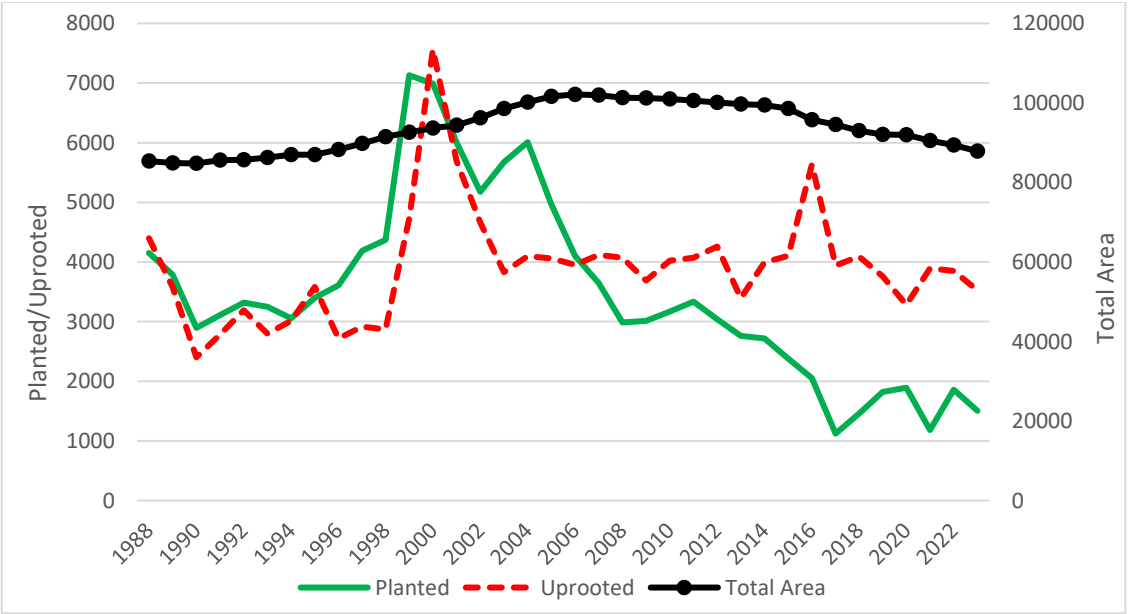


Figure 3.5: Annual total vineyard area (right-axis) and planted vs uprooted hectares (Adapted from: SAWIS, various years)

Table 3.1: Important wine industry measures since 1995 (Adapted from: Anderson and Pinilla, 2017; Vink *et al.*, 2018; SAWIS (various years).

Measure	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2023**
Number of wine farmers	4634	4501	4360	3596	3314	3222	2872
Private cellars	183	277	495	493	485	457	451
Number of grape growers	4451	4224	3865	3103	2829	2693	2350
Producer cellars	71	69	65	54	49	45	45
Producer wholesalers	5	9	21	26	25	27	26
% cellar that crush <100 tonnes	-	30	51	46	40	40	42
Winegrape vine area ('000 ha)	84	94	102	101	99	92	88
Average farm size (ha)	18.1	20.8	23.3	28.1	29.8	28.6	30.6
Vines < 4 years as % of total	-	19.4	14.1	7.7	6.5	8.9	9.5
Domestic sales (ML)	371	389	345	346	383	314	464
Export's share of production (%)	15	20	39	40	35	35	40
Share of crop that is red (%)	10	15	31	35	37	35	34

From 1995-2023 the number of wine farmers has decreased nearly 40%, from 4634 to 2872 (Table 3.1). The number of private cellars has more than doubled, while producer cellars have decreased by a third, indicating a rise in independent winemaking and a shift away from cooperative structures. Domestic consumption exhibits reasonable growth, with the export share of production more than doubling, reflecting increased market integration. The share of red wine seems to have stabilized around 35% since 2010, suggesting a balance between demand for red and white varietals.

In 2022, only 12% of farmers earned more than the suggested net farm income required for economically sustainable production (FTI, 2024). The average industry production cost for the 2023 season increased by 5.3% to R70,974 per hectare, slightly less than the long-term average of 7% (Vinpro, 2024). The break-even price is the amount required to cover production costs, excluding entrepreneurial remuneration, interest, or tax. The break-even price is calculated by dividing the total production cost by the average yield per hectare. The industry average break-even point increased by 24% to R4,392 per tonne in the 2023 production year (Figure 3.5). Greater yields reduce the break-even price; however, this is made difficult due to ageing vineyards that produce less (Vinpro, 2024).

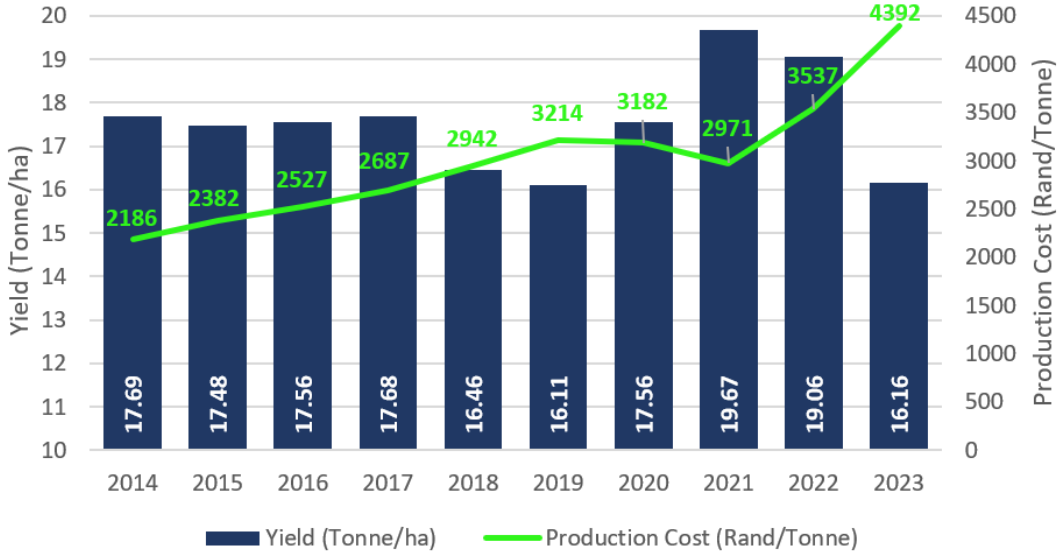


Figure 3.6: Industry break-even price per tonne (Source: Vinpro, 2024).

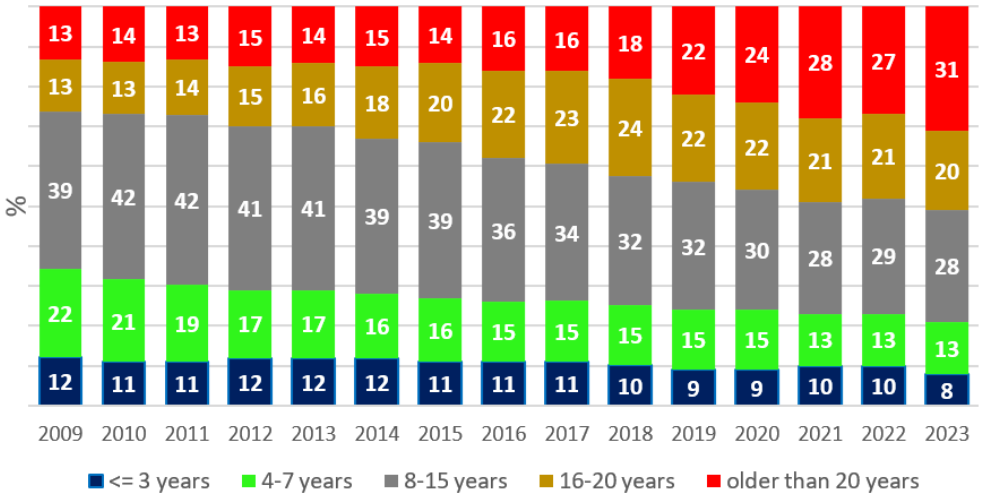


Figure 3.7: Age distribution of vineyards, 2009-2023 (Source: Vinpro, 2024).

Volatile average gross income has limited producers' ability to replant old vineyards. According to Vinpro (2024b:22), "the ageing of vineyards in the industry has entered a dire situation this year". Approximately 8% of vineyards are younger than four years, deemed young vines, the lowest percentage for this category in more than two decades. Additionally, old vines - vineyards older than 20 years - have reached 31%, the largest proportion in the same period. Therefore, for the first time, vineyards older than 16 years make up the majority of total hectares (51%). However, this age distribution is of less concern to private cellars whose primary objective is quality rather than yield volume. A similar trend is evident in several EU wine-producing countries where the prevalence of old vines is well established. According to Carbone, Quici, and Pica (2019), vineyards older than 30 years constitute at least 30% of the total in many regions of the EU, while those younger than 10 years make up less than 20%.

Older vines can produce more concentrated fruit but yield considerably less and are worse affected by fungal diseases and suboptimal weather conditions (Vinpro, 2024b). Reports indicate that many older vineyards produced no crop for the 2023 season. The vineyard surface aged between four and 15 years is shrinking annually, creating a problem in terms of raw product security. These observations are contrary to the prescribed norm that 15% of the vineyard surface area should be comprised of young vines, with the proportion of old vineyards not exceeding 15% (Vinpro, 2024b). Every region currently has a greater proportion of old vines relative to young vines, and the ratio of old to young vineyard areas across the Western Cape almost tripled since 2009.

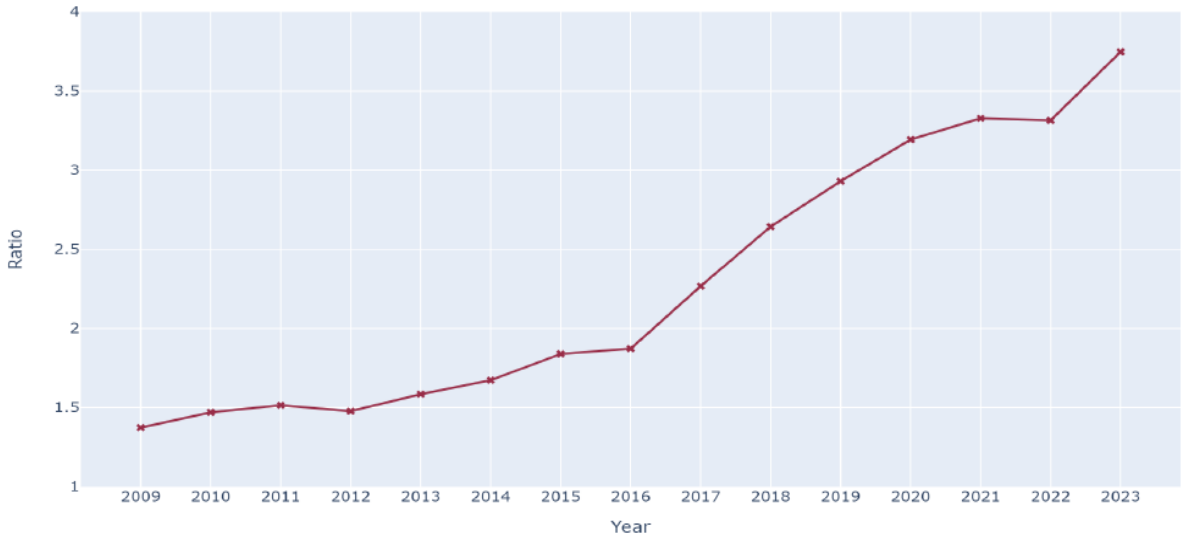


Figure 3.8: Ratio of old to young vineyard area (Adapted from: SAWIS, various years)

4. Data and Methodology

4.1 Research Design

This paper investigates the effect of weather on wine quality, using wine ratings from recognized critics and auction price data as a proxy for quality. A Multiple Linear Regression model is estimated using Ordinary Least Squares, assuming independently and identically distributed errors. The study focuses on the Stellenbosch wine district, specifically evaluating flagship Bordeaux-style wines (Appendix E) from 2001 to 2021 vintages. Data pre-processing, descriptive statistics, and visualizations are done using Python, with the *statsmodels* library used to model the effects of climate on critic ratings and auction prices.

The independent variables used to predict wine quality are derived from temperature and precipitation data recorded at the Stellenbosch and Jonkershoek weather stations supplied by the South African Weather Service. Jonkershoek records daily temperatures and rainfall, while the Stellenbosch weather station only records rainfall. The climate variables used in the regressions are defined in Table 4.1. The temperature and rainfall parameters used in this paper are the same as those employed by major contributors to the literature (e.g. Ashenfelter, Ashmore, and Lalonde, 1995; Byron and Ashenfelter, 1995; Jones et al., 2005; Ramirez, 2008).

Table 4.1: Climate variable definitions.

Climate Variable	Units	Definition
GSAT: growing season average temperature	°C	Average daily temperature from 1 October to 31 March.
GSDT: growing season diurnal temperature	°C	Average daily difference between min and max temperatures from 1 October to 31 March.
Harvest Rainfall	mm	Cumulative rainfall for January and February.
Winter Rainfall	mm	Cumulative rainfall from 1 April to 30 September

Wines can be produced from grapes sourced across the country, and in some cases, blended across multiple harvest years to create non-vintage wines. This raises the question: how can regional weather be linked to wine quality ratings? The answer lies in the Wine of Origin (WO) system, introduced in 1973 and modelled after France's Appellation d'Origine Contrôlée (AOC). The WO system guarantees that a wine is made from the specified district's grapes, in the year which the climate is experienced by the vine, as stated on the label (WOSA, 2024).

In terms of the naming convention, if all grapes grown for a specific wine are from Banghoek, then it is permissible to state "WO Banghoek" on the label. If for instance the wine is a blend of grapes from both Banghoek and Bottelary, the over-arching district name must be used, hence "WO Stellenbosch". In both examples, the wines qualify for the analysis as the constituent grapes were grown within the recognised Stellenbosch district.

The wines analysed are made from a single varietal, or multiple varietals used in a Bordeaux-style red blend. These varietals include Cabernet Sauvignon, Merlot, Cabernet Franc, Petit Verdot, or Malbec. Crucially, for a wine to bear a varietal name, at least 85% of its composition must come from that grape (WOSA, 2024). These cultivars share similar optimal temperature profiles, ensuring consistent comparison regardless of individual cultivar selection and blending proportions. Additionally, this cultivar-district combination offers one of the most extensive collections of South African wine ratings, ensuring robust data representation.

4.2 Data

4.2.1 Independent Variables: Weather data

The growing season is defined as the period spanning the start of October to the end of March. The grapes are harvested at the end of the growing season, usually from mid-January depending on the cultivar. It is important to note that a bottle's vintage matches the year the grapes were harvested. Consequently, even though the growing season started in October 2023, the wine's vintage is stated as 2024 since the grapes were harvested at the end of the season in the following year. The Growing Season Average Temperature (GSAT) of a vintage therefore has components from two calendar years, although a single vintage is quoted.

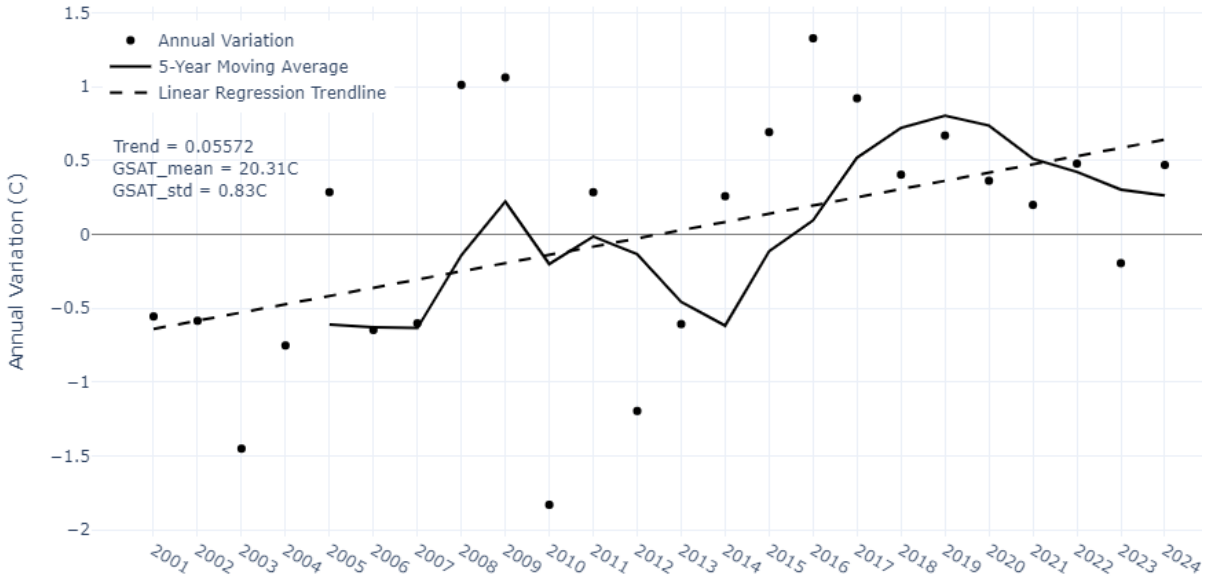


Figure 4.1: Stellenbosch's GSAT trend, mean and standard deviation calculated for the period 2001-2024.

The mean GSAT since 2001 is 20.31°C with a standard deviation of 0.83°C. Each annual data point is represented as the variation from the mean GSAT. The 2010 season had the coolest GSAT in the period (18.47°C), with 2016 being the hottest (21.63°C). The line of best-fit acts as the GSAT trend and has a value of 0.056. That is, on average, we expect each subsequent year's GSAT to be 0.056°C hotter than the previous. This can be interpreted as a more than half-a-degree centigrade increase in Stellenbosch's GSAT every 10 years. Additionally, ten out of the previous eleven years had a higher-than-average GSAT. This is a continuation of the trend identified by Bonnardot and Carey (2008) who reported a significant increase in the annual temperature values for Stellenbosch from 1976 to 2006 (Figure 4.2).

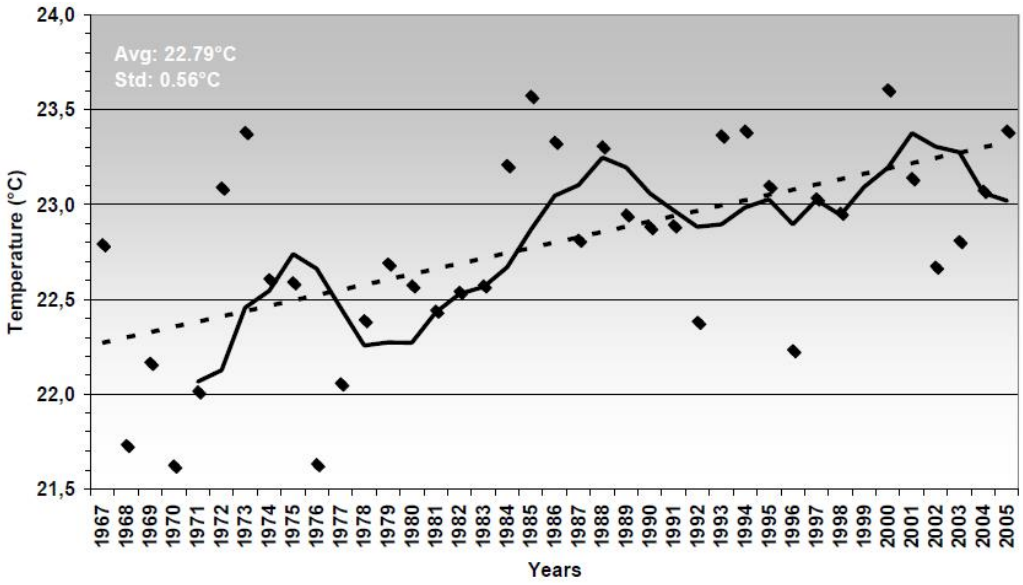


Figure 4.2: Annual maximum temperatures for Stellenbosch between 1967 and 2006 (Source: Bonnardot and Carey, 2008).

Diurnal temperature (GSDT) refers to the daily difference between the observed maximum and minimum temperatures. This is calculated for the same growing season period from October to March. The GSDT for 2009, whose vintage is arguably the best that Stellenbosch has produced across most varieties (Robinson, 2024), is a clear outlier. The mean GSDT since 2001 was 14.97°C with a standard deviation of 0.8°C, while 2009 was almost 3°C higher at 17.93°C.

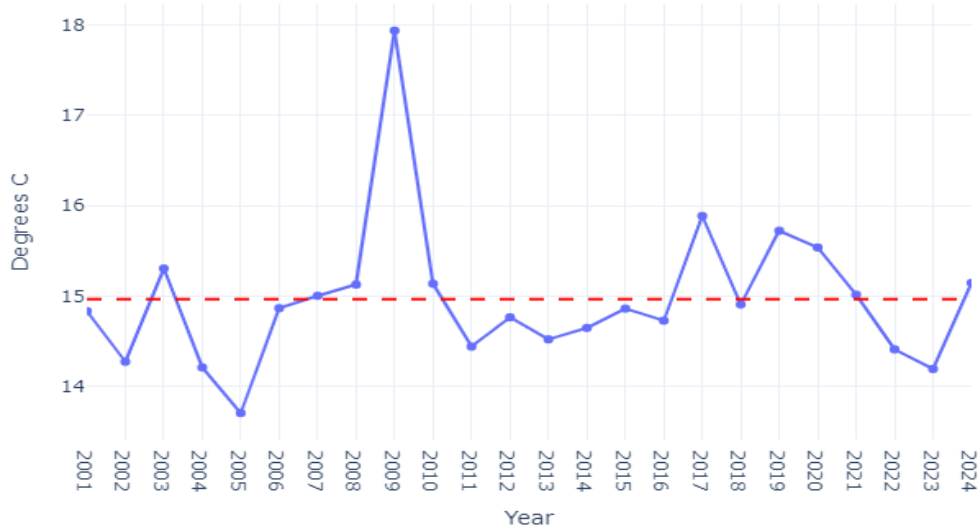


Figure 4.3: Mean GSDT for Stellenbosch, 2001-2024.

Both the Stellenbosch and Jonkershoek weather stations contain rainfall data. The primary Stellenbosch weather station contained missing values for multiple days. To retain continuity in the dataset, daily rainfall values were averaged between the Stellenbosch and Jonkershoek stations. Although Jonkershoek's rainfall levels are higher overall (Figure 4.4), the use of a combined average was considered to approximate regional rainfall. This method aimed to provide a more complete representation of total rainfall, rather than relying solely on a single station with incomplete data.

If both stations had recorded rainfall on a day, the average was calculated for the region. If a station had a missing record for a day, the rainfall from the other station would be used as the rainfall for the region. There were zero cases where both stations had missing rainfall records on the same day. The

rainfall data for Stellenbosch and Jonkershoek exhibit a significant correlation at the month level, with a Pearson correlation coefficient of 0.92.

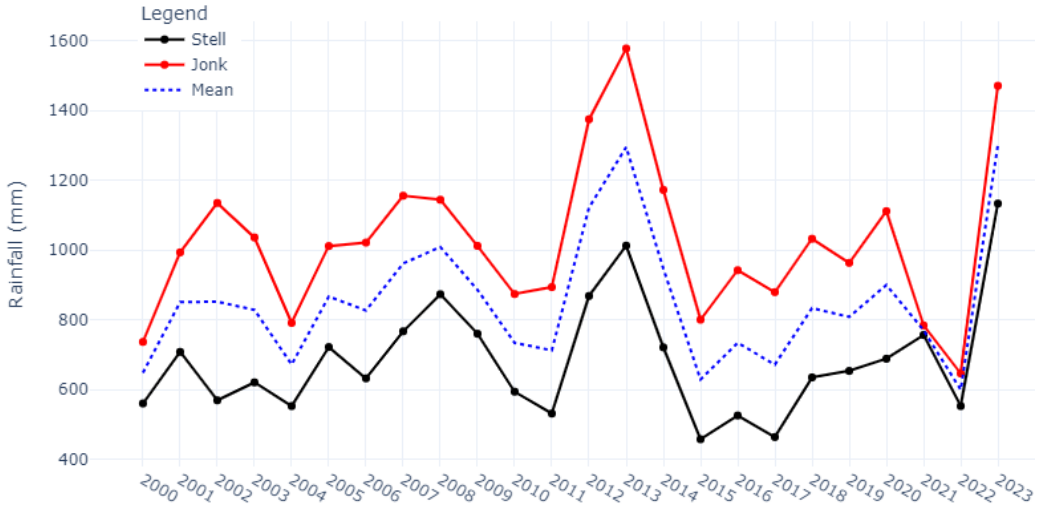


Figure 4.4: Annual rainfall for the Stellenbosch and Jonkershoek Weather Stations, 2000-2023.

Cumulative rainfall during the two main harvest months (Figure 4.5) negatively impacts grape quality (Ashenfelter, 2008). A clear outlier here is 2002 with 146mm versus an average of 40mm. Renowned wine critic and Master of Wine Jancis Robinson described the 2002 vintage as follows: “Rain in abundance, leading to plentiful rot. Not a good vintage.” In contrast, the exceptional 2009 vintage, marked by notably low harvest rainfall - a favourable condition for quality - earned Robinson's high praise, who remarked that it received “universal acclaim across all varieties.” (Robinson, 2024).

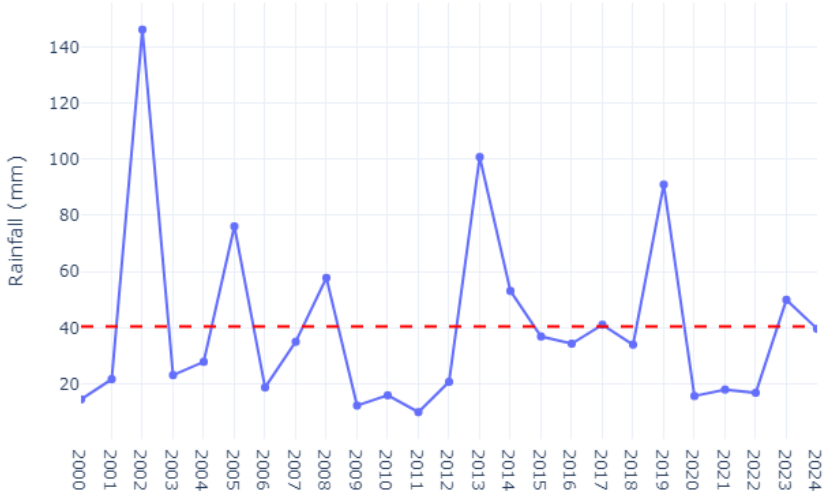


Figure 4.5: Annual harvest rainfall for 2000-2024, mean rainfall marked with a dashed line.

Table 4.2: Correlation coefficients of weather variables analysed (n=24).

Weather Variable	1	2	3	4	5	6
1 Jan_Feb rain (mm)	-					
2 Jan_Feb_Mar rain (mm)	**0.71**	-				
3 Previous winter rain (May-Aug)	0.19	0.06	-			
4 Previous winter rain (Apr-Sept)	0.23	0.06	**0.89**	-		
5 GSAT	0.03	-0.12	0.02	0.04	-	
6 GSDT	-0.28	-0.32	0.22	0.25	0.30	-

Bold values indicate coefficients with $p < 0.01$.

A correlation analysis is conducted across the different climate variables (Table 4.2). The two harvest rainfall variables are highly correlated and statistically significant at the 1% level, the difference between the variables is in the inclusion of March rainfall in the summation. Similar correlations exist for the winter rainfall variables, with May-August deemed the *core* winter rainfall and April-September considered the *extended* winter rainfall.

4.2.2 Heat Summation Indices

Amerine and Winkler (1944) studied the climatic suitability of more than 150 grape cultivars at various temperatures between 1935 and 1941. They developed the Winkler Index, designating regions based on their degree-day summations. Degree-days are the sum of daily average temperatures above 10°C during a growing season, October 1 – March 31 in the Southern Hemisphere.

$$\text{Winkler Index} = \sum_{i=01.10}^{n=31.03} (\mathrm{T_{mean,i}} - 10)$$

Table 4.3: Degree-day regions and classes (Source: Annerine and Winkler, 1944).

Degree-days (°C)	Region	Class
850-1389	I	Cool
1390-1670	II	Moderate
1671-1949	III	Warm
1950-2220	IV	Hot
>2220	V	Very Hot

Vink *et al.* (2012) reported the Winkler Index for the Paarl Wine of Origin district, a northerly neighbour of Stellenbosch, from 1941-2008. Figure 4.6 indicates a distinct change in the temperature regime for Paarl from 1998 onwards. Each of the last ten seasons analysed (1999-2008) experienced above-average warming in terms of the Winkler Index (Vink *et al.*, 2012).

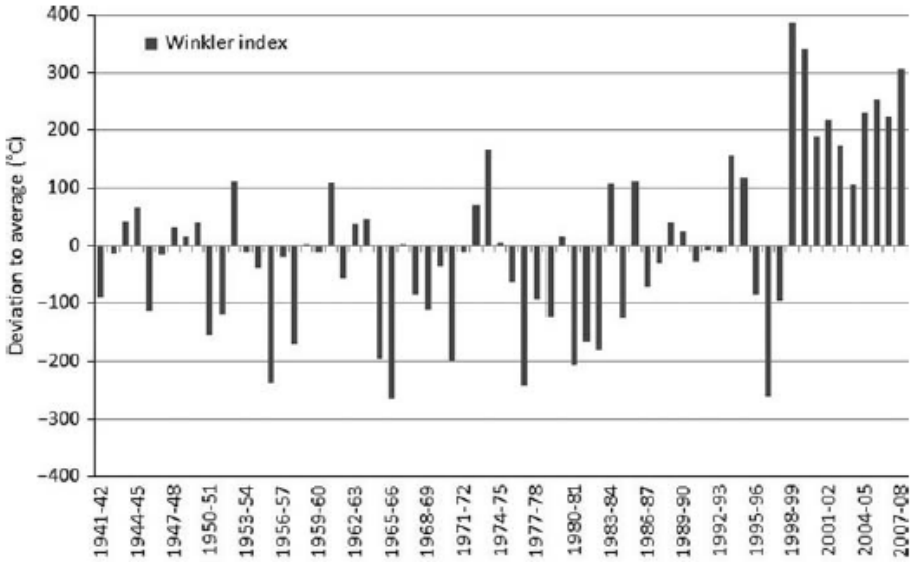


Figure 4.6: Winkler Index in Paarl expressed as the deviation from the 1941-2008 average (Source: Vink *et al.*, 2012).

This paper finds a similar pattern of the change in the Winkler Index for Stellenbosch from 2001-2024. The approach of calculating the Winkler and Huglin indices is slightly altered; instead of using the conventional seven-month summation, the reported summation occurs from 01 October to 31 March. The alteration was made based on the comments from an anonymous contributor within the viticultural industry. The reasoning is that warming has brought harvest dates forward such that very

few cultivars are picked in April, rendering April temperatures less important. The six-month period also conveniently aligns with the length of the GSAT variable. Ten of the last 11 vintages experienced an above-average number of growing degree days.

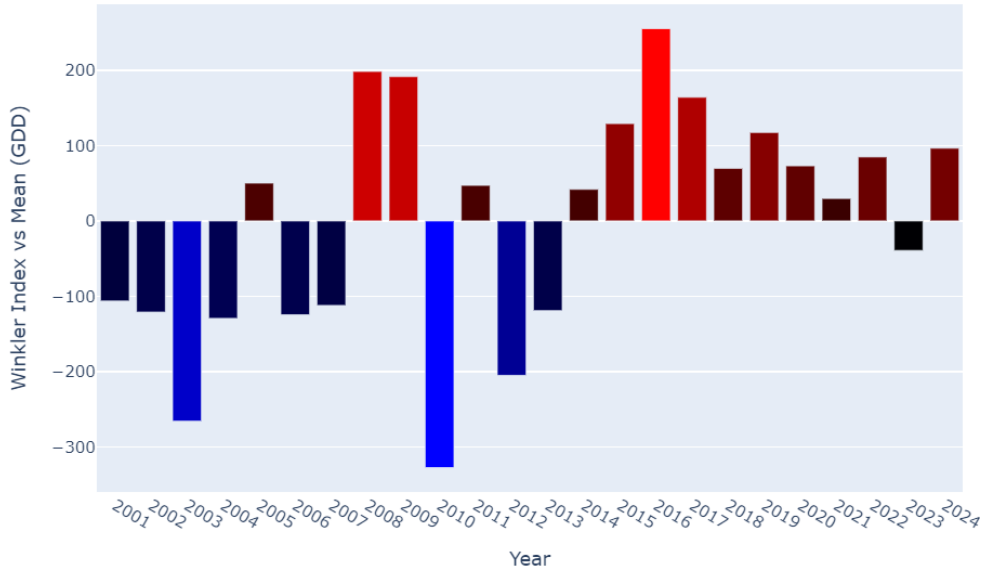


Figure 4.7: Annual variations from the mean Winkler Index for Stellenbosch, 2001-2024.

The Huglin Index, a similar metric also measured in degree-days, sums the average daily maximum and mean temperatures above 10°C after applying a latitude correction factor of "K" (Huglin, 1978). Since only a single region is analysed, the correction factor is ignored. Over the 2001-2024 period, Winkler and Huglin indices have on average increased by 10.3 and 10.8 growing degree days per year (Appendix D).

$$\text{Huglin Index} = \sum_{i=01.10}^{n=31.03} K\left[\frac{(\mathrm{T_{mean,i}}-10)+(\mathrm{T_{max,i}}-10)}{2}\right]$$

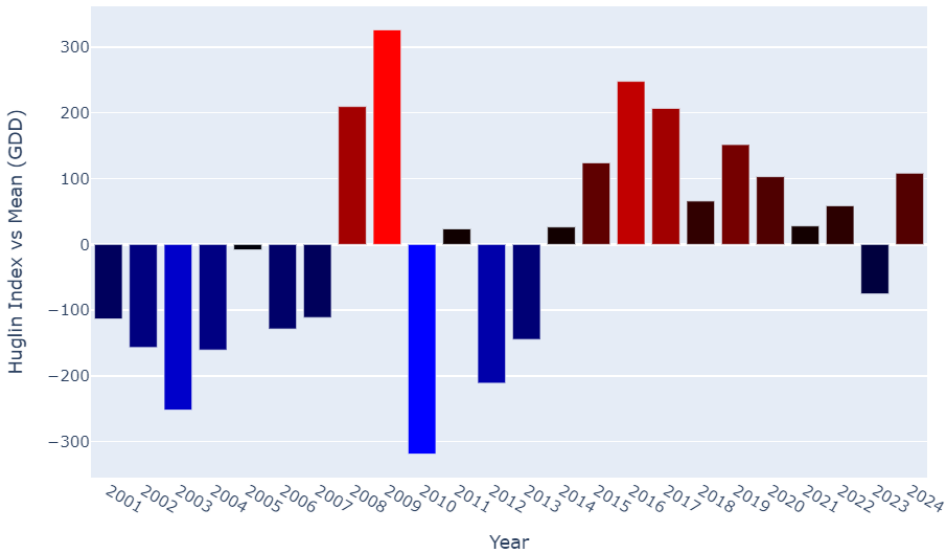


Figure 4.8: Annual variations from the mean Huglin Index for Stellenbosch, 2001-2024.

Smart and Dry (1980) propose the Mean January Temperature (MJT) as a measure of warming. De Villiers *et al.* (1996) studied the division of Western Cape Pinotage cultivation areas into climatic regions using Mean February Temperatures (MFT). Distinct increases for both MJT and MFT are found from 2011 onwards in Stellenbosch. Figure 4.9 describes the number of hot days above 30°C and 35°C respectively. Very hot days are associated with increased sunburn which can cause significant losses in quality and yields of wine grapes (Gambetta *et al.*, 2021). Greer and La Borde (2006) find that sunburn affects up to 15% of total wine grape production, and Calderon-Orellana *et al.* (2018) found up to 40% of sunburn damage for sensitive cultivars in Chile. Interestingly, 2009 experienced the highest number of hot days, which one might expect to be detrimental to the vines. However, it is widely regarded as the district's finest vintage. Stellenbosch has on average 61 days above 30°C and 14 days above 35°C annually.

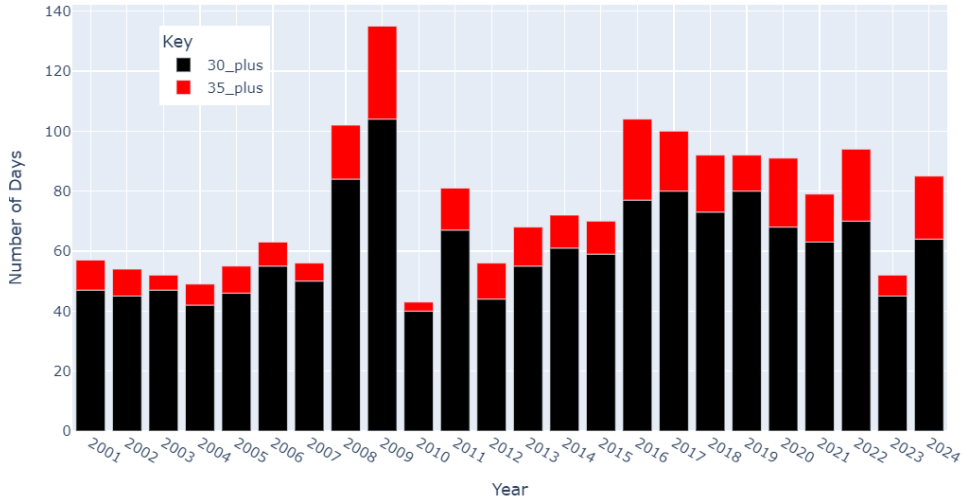


Figure 4.9: Number of days above 30°C and 35°C for Stellenbosch, 2001-2024.

The number of days above 30°C variable is strong and positively correlated at the 5% significance level with days above 35°C, Winkler, and Huglin indices (Table 4.4). Unsurprisingly, due to the similarity of the summations, the Huglin and Winkler indices exhibit an almost perfect correlation. The mean temperatures in January and February respectively (MJT and MFT) display a weak correlation across all variables.

Table 4.4: Correlation coefficients of weather variables analysed (n=24).

Heat Variable	1	2	3	4	5	6
1 WI	-					
2 HI	**0.96**	-				
3 MJT (C)	0.25	0.09	-			
4 MFT (C)	0.47	0.33	-0.18	-		
5 30_plus	**0.76**	**0.90**	-0.16	0.16	-	
6 35_plus	0.49	0.64	0.10	-0.23	**0.78**	-

Bold values indicate coefficients with $p < 0.05$.

4.3 Dependent Variable: Wine Quality

Compiling a dataset of wine ratings for Stellenbosch's Bordeaux-style wines is complicated as there are numerous rating publications and wine critics to choose from, both local and international. Given the focus on Bordeaux varietals and blends in Stellenbosch, it makes sense to select ratings from critics familiar with Bordeaux wines, i.e. international wine critics.

This wine-style criterion narrows potential data sources to certain critics and tasting organizations. These international critics, with their experience evaluating the best wines, are likely to offer a broader range of scores for South African wines than local critics. The following section outlines each rating source considered.

A limitation of the final ratings dataset is the inconsistency among judges, which cannot be fully accounted for. Each publication and critic have a unique palate and preference, and some tasters are stricter than others, assigning a wine 90 points where others might award 95. Ideally, one would focus on a single critic's ratings for Stellenbosch Bordeaux varietals since 2000; however, very few critics cover South African wines comprehensively.

The most notable exception is Tim Atkin, a Master of Wine, who has become a leading critic of South African wines, with producers eagerly awaiting his annual ratings. His tastings are compiled in his South African Special Report, where wines scoring 95+ points experience heightened demand upon the report's release. Each report costs R400 and covers 12 vintages (Atkin, 2024). However, his ratings only cover half of the period of analysis and access to the data requires purchasing every report.

Cellar Tracker
Cellar Tracker is an open-source, community-based platform where members rate and review wines. Founded in 2003, it has over 4.7 million reviews and 12 million tasting notes from enthusiasts and professionals, covering entry-level wines to high-end collector's items (Cellar Tracker, 2024). The site also allows users to track wines they've tasted and log data such as vintage, tasting notes, and price. Cellar Tracker offers the broadest range of wine ratings, often reviewing products ignored by other rating institutions. This makes it a valuable resource for entry-level and mid-priced wines. However, since users aren't vetted, ratings can be inconsistent due to varying levels of wine expertise. Unlike other rating agencies that taste wines upon market entry, Cellar Tracker accepts reviews at different stages of bottle maturation. For example, while most wines are tasted upon release (typically two years post-vintage), Cellar Tracker users may submit ratings anywhere from release to 20-plus years after release. This variation makes comparing ratings challenging, as they may be influenced by bottle ageing and maturation.

Wine Spectator
Established in 1976, Wine Spectator is one of the most influential wine publications. Its tasting team comprises experienced critics who conduct tastings blind (Wine Spectator, 2024). A blind tasting entails withholding vital information from a critic, like winemaker, region, varietal, or vintage. Wine Spectator's endorsement significantly impacts a wine's popularity. Wine Spectator covers wines worldwide but has limited ratings for entry-level wines. Access to ratings requires a subscription, and some critics argue that its commercial relationships favour mainstream producers over smaller labels.

WineSearcher
Founded as a price-comparison website in 1999, WineSearcher expanded to include wine and spirit reviews and ratings to the public. The site facilitates 240 million searches annually across 20 million products (WineSearcher, 2024a). WineSearcher aggregates ratings from enthusiasts, independent critics, and respected publications, providing a broad spectrum of opinions. Its primary feature is the combination of price comparisons with ratings, enabling consumers to make informed purchases. A bottle's overall rating reflects the average score across critics and publications.

James Suckling
Formerly an editor at Wine Spectator, Suckling left to pursue a career as an independent critic. His coverage of wines tasted is broader than the Wine Advocate's, including New World wines which are often overlooked by the mainstream (James Suckling, 2024). After Rober Parker's retirement, Suckling has become arguably the leading wine critic but has come under fire for his overly positive, if not generous ratings of wines. His critics often quote him as being the lead antagonist perpetuating the phenomenon of *rating inflation*.

Decanter
Decanter is a UK-based publication that provides reviews from blind tastings by a panel of Masters of Wine. Tasters are only informed of the wine's price band. The reviews are generally more technical than other sources and access requires a paid subscription. Decanter's strength is its specialisation of European wines, this unfortunately means that wines from New World producers like South Africa have very little coverage.

Of the five data sources identified, ratings from James Suckling and Decanter were excluded from the analysis as they both lacked sufficient coverage of wine ratings.

The annual vintage rating per source is comprised of ratings from that vintage. For example, if Wine Spectator had 50 ratings of Stellenbosch Bordeaux Blends for the 2020 vintage, the average of those ratings is taken as the "vintage rating". The vintage ratings for Cellar Tracker, WineSearcher and Wine Spectator depicted in Figure 4.10.

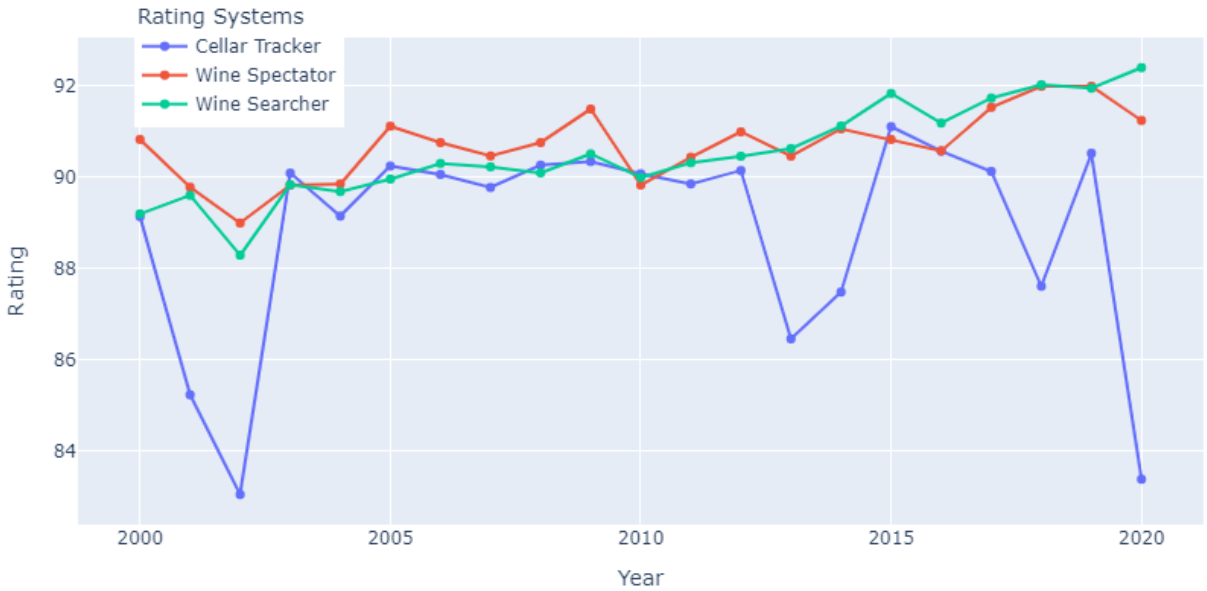


Figure 4.10: Annual vintage scores for Cellar Tracker, Wine Spectator and WineSearcher.

Upon investigating the three main rating candidates, it was evident that Cellar Tracker potentially contained erroneous or questionable reviews which affected the average vintage rating. Its ratings seemed unreliable for certain vintages. Unlike Wine Spectator and WineSearcher, Cellar Tracker accepts ratings from amateur wine enthusiasts. The presence of non-professional scores and potentially bad actors could therefore be the cause of these anomalies. Cellar Tracker was subsequently omitted from the final ratings data. The final vintage rating was calculated as the mean vintage score of WineSearcher and Wine Spectator.

Across both rating agencies, 33 wines are identified. Many other wines were considered; however, they were rated too infrequently. The minimum criteria for a wine to be included in the dataset is at least 50% coverage for the period. The average number of ratings for each bottle in the dataset was 17.3 over the 2001-2021 period, which is comprised of 571 individual bottle ratings (Appendix E).

If both agencies have a rating for a wine, the average is used; if only a single agency has a rating, that rating is used. If a bottle does not have a rating for a year, it is omitted from the vintage rating for the year in question. The overall vintage rating for a year is the average of the constituent bottle ratings.

WineSearcher has double the amount of Wine Spectator ratings. Their coverage is better as they pool ratings from multiple critics and rating agencies, whereas Wine Spectator is constrained to a single team of tasters. The descriptive statistics in general are very similar, with Wine Spectator having a slightly larger standard deviation of 1.98, compared to 1.80 of WineSearcher. Although both agencies provide scores out of 100, it appears that Wine Spectator rates wines across a larger spectrum of scores. Both sources have similar lower, median, and upper percentiles suggesting consistent clustering of ratings. The two most popular scores for Wine Spectator and WineSearcher are 91 and 92, and 90 and 91 respectively.

Table 4.5: Descriptive statistics of ratings for Wine Spectator and WineSearcher.

Statistic	Wine Spectator	WineSearcher
count	284	561
mean	90.65	90.68
std	1.98	1.80
min	84	85
25%	89	90
50%	91	91
75%	92	92
max	95	98

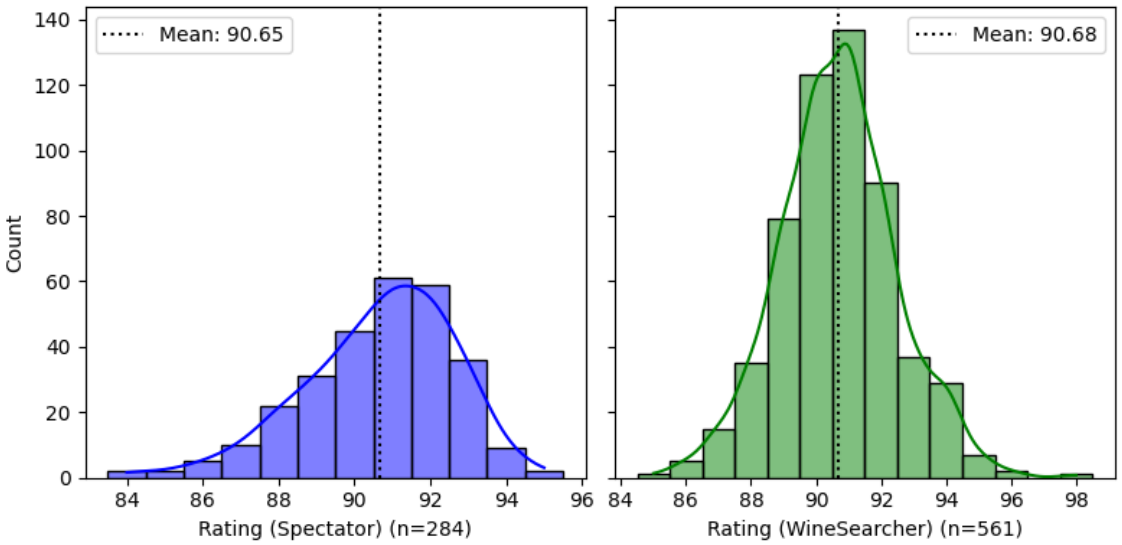


Figure 4.11: Distribution of scores from Wine Spectator and WineSearcher.

Graphs of annual ratings from the two agencies for the same bottle of wine are plotted with correlation coefficients and p-values reported (Appendix F). Only the period 2001-2018 is considered as from 2019 onwards there is considerably less overlap in wines rated by both agencies. The correlation of scores at the wine-year level is r = 0.610 which is significant at better than 0.01%. WineSearcher ratings vary less than Wine Spectator, indicating a conservative rating approach by the former. There seems to be a systematic difference in the scoring philosophies or tasting methodologies. This might be attributed to the Wine Spectator team tasting blind, whereas the scores from WineSearcher are pooled from multiple critics who do not declare what type of tastings they conduct.

A scatter plot of annual ratings by both agencies is displayed in Figure 4.12. The 2002 (Spectator: 89, Searcher: 88.3) and 2021 (Spectator: 92.5, Searcher: 93.3) vintages are removed due to being outliers. Labels are assigned based on K-means clustering with n=3 into either a top, mid, or bottom tier. Reported but not shown is a line of best fit with a gradient of 0.96 and a correlation coefficient of 0.75 which is significant at better than 0.01%. The strong correlation between the two rating agencies indicates a high level of agreement in their assessment of wine quality across vintages.

It seems mostly true that early 2000's vintages cluster within the bottom tier, and recent vintages cluster within the top tier. The removed outliers also follow this trend; 2002 clusters with the bottom tier, and 2021 clusters with the top tier. Either winemaking techniques, farmer knowledge, labour relations, farm efficiency, growing conditions, or other production-related factors are improving with time, or rating inflation by overly generous wine critics is to blame, or a combination of the two are present.

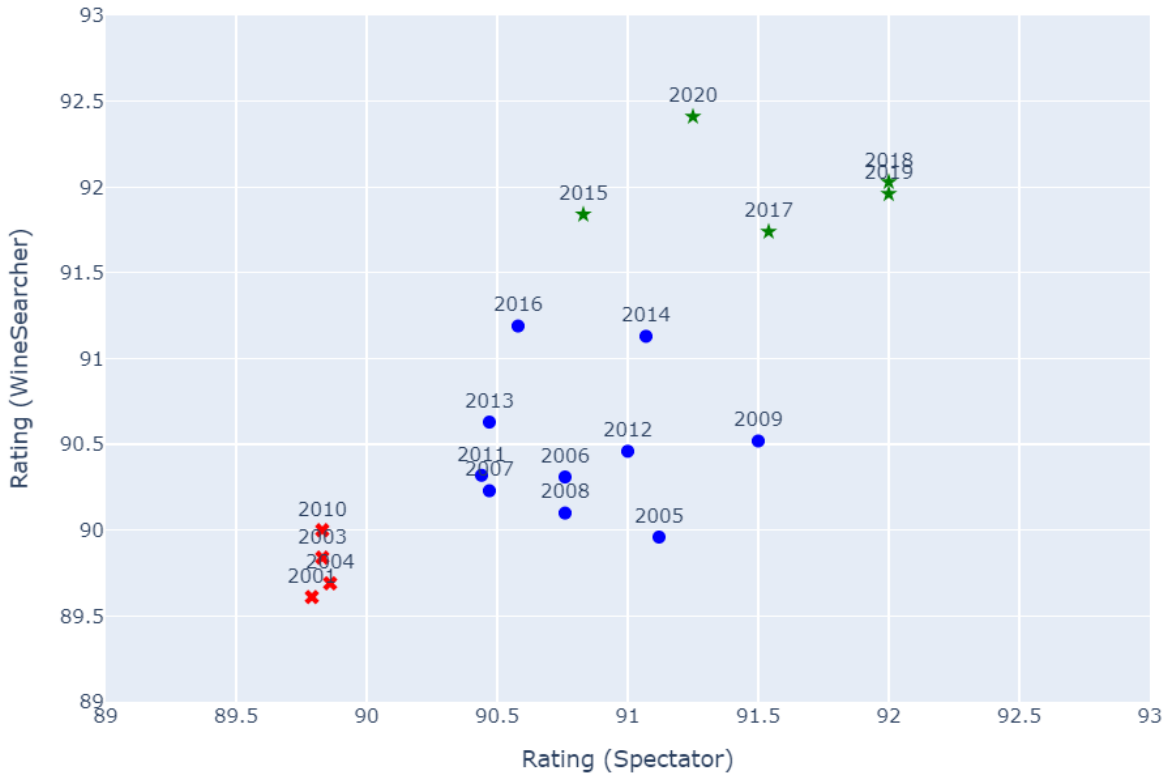


Figure 4.12: Clustering of Stellenbosch vintages from 2001-2021 based on the respective ratings with labels: Top (star), Mid (circle), and Bottom-tier (cross). The outlier vintages of 2002 and 2021 excluded.

4.4 Rating Inflation

The phenomenon of increasing annual wine ratings is known as rating inflation (Kotonya *et al.,* 2018). In general, the increase in the quality of a wine can be explained by favourable climatic conditions, improved wine-making techniques, or modernising viticulture practices. Figure 4.13 illustrates the upward trend of ratings for the portfolio of Stellenbosch Bordeaux-style wines analysed.

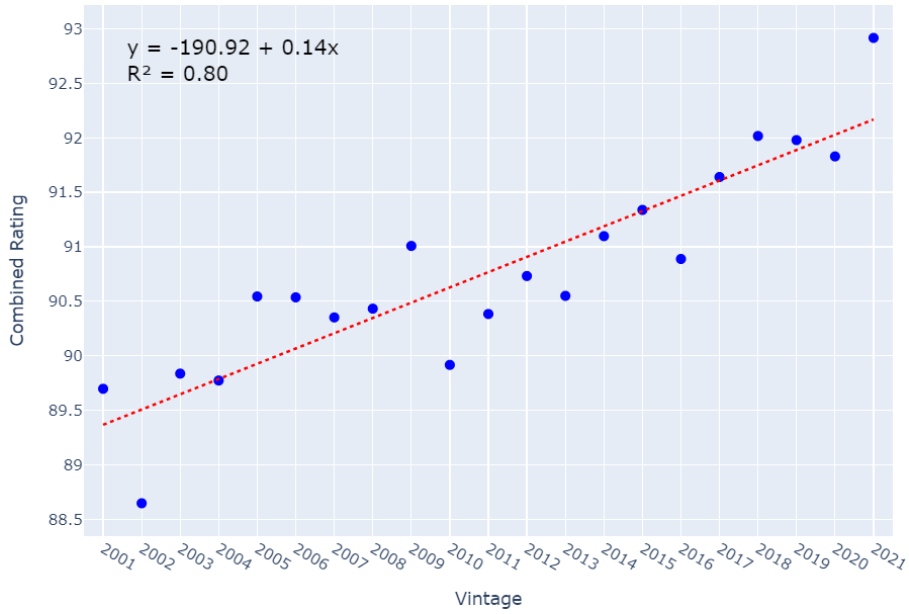


Figure 4.13: The upward trend of Vintage Rating for the portfolio of Stellenbosch wines.

The gradient of the line of best fit is the average increase in rating points per vintage. In this case, it was found to be 0.14, which can be interpreted as an increase of 0.14 rating points per vintage, or 1.4 rating points for every 10 vintages. This prompted an analysis of rating inflation in Old World vs New World wine-producing countries. The goal is to compare rating inflation for the portfolio of Stellenbosch wines against the rating inflation experienced elsewhere.

For this exercise, the Old World wine-producing countries assessed are France, Italy, and Spain, while the New World wine-producing countries refer to South Africa, the USA, Australia, New Zealand, Chile, and Argentina. Ratings for each country were taken from the Wine-Searcher Global Wine Vintage Chart and aggregated by region (WineSearcher, 2024).

The expectation is that Old World winemakers, being more knowledgeable and experienced, make less annual progress in viticulture and oenology practices compared to their New World counterparts. Consequently, New World producers are likely to experience greater rating inflation, having made more significant advancements over the past two decades than their European counterparts.

WineSearcher considers bottle prices as mid-range from £30/R650 to £100/R2260 and fine wine up to £250/R5650. Of the Stellenbosch wines analysed, the vast majority fall within the *mid-range* bracket, although mid-range is somewhat of a misnomer in the South African context. Locally, these wines would be considered ultra-premium, which speaks to the value that South African wines offer.

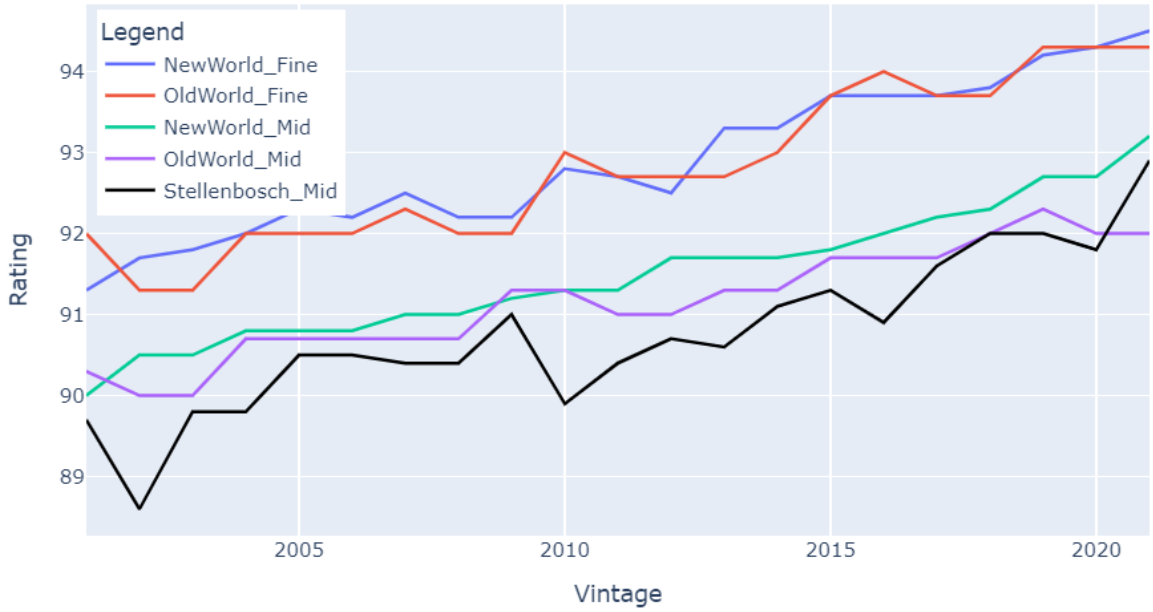


Figure 4.14: Rating inflation grouped by Old World or New World wine-producing countries, by mid-priced or fine wine categories, 2001-2021 (Adapted from: WineSearcher, 2024b).

Of the mid-priced wines, the Stellenbosch wines analysed are experiencing stronger rating inflation than both new and old world counterparts (Table 4.6). All fine wines are experiencing rating inflation that exceeds any region in the mid-priced tier. A study by Sadras *et al.* (2007) found that during the period 1980-2005, 24 Australian wine regions experienced average rating inflation of 0.09 points per year. More significant rating inflation is presented by Jones *et al.* (2001) for California with an average increase of 0.22 points per year for Sotheby's wine ratings, and similar results for Robert Parker's scores in Wine Advocate (Parker, 1997). Jones *et al.* (2005) reports a higher vintage rating trend of 0.32 points per year, statistically significant at the 5% level.

Table 4.6: Rating gradient by wine region and wine price classification. Rating inflation is given in points out of 100 per year (Adapted from: WineSearcher, 2024b).

Region: Wine	Rating Inflation
old world: Fine	0.150
new world: Fine	0.147
Stellenbosch: Mid	0.140
new world: Mid	0.131
old world: Mid	0.103

Across the world, wine quality is increasing at a rate of at least 0.103 points per year, or a full point per 10 years (Table 4.6). Could it be that the world's wine is objectively becoming better, or is something else at play? This often sparks a debate regarding the nature of ratings and the fact that critics are more liberal with rewarding high scores than before.

Goode (2024) recalls a time when Rober Parker's *Wine Buyer's Guide* indicated that a wine score of 85 meant the wine was worth seeking out. According to Goode (2024):

> "In the past, you'd have to make a decent wine to score 85. And 90 scores used to be a cause of celebration for a winemaker, whereas now it feels a bit like a fail. 95 is the new 90, some are saying."

He adds, “Now the scale shifted significantly, and scoring is in a much narrower range” (Goode, 2024). Since scores have an upper threshold of 100 points, rating inflation causes the range of possible scores to be compressed.

Esteemed wine writer and critic Michael Fridjhon reflected on historic *Wine Advocate* ratings, stating (Fridjhon, 2017):

> “I don’t remember many wines scoring under 75, but in the early days, most wines sat in the mid-80s. A retailer famously commented that anything that Parker scored under 90 he couldn’t sell, and anything over 90 he couldn’t buy (i.e. it was unobtainable).”

He also noted the shift in scoring standards, observing, “In the past decade we have witnessed a massive devaluation in the currency of wine scores.” (Fridjhon, 2017). Producers naturally highlight a wine’s highest ratings, as it bolsters consumer interest and engagement. On the topic, Ashenfelter (2008:184) states:

> “It is common for the proprietors to claim that each vintage is a good one, independent of the weather that produced it. Indeed, there is no obvious incentive for an individual proprietor to ever claim anything else!”

Critics, in turn, benefit from assigning higher scores, as it enhances their relevance and visibility.

Perhaps the only way that critics can earn the trust of consumers is by conducting blind tastings. James Laube from Wine Spectator boasts that in thirty years he has only given two perfect scores. He further adds that in 2012, Wine Spectator assessed 17000 wines, none of which received a 100-point score (Laube, 2013). He claims that wine reviewers fall into one of two camps, those who taste blind, and those who do not. The implication is that non-blind tasters have implicit knowledge of the wine and fall victim to expectation and confirmation biases. Laube (2013) is proud of his team’s efforts to taste blind, as it is costly and time-consuming. He states, “It's far easier and less expensive for a reviewer to taste wines at an industry-sponsored event or on-site at the wineries (or even in winemakers' homes) than it is to set up a controlled blind tasting of the same wines.” (Laube, 2013). This, he argues, is the root of escalating ratings and the abundance of 100-point wines.

Section 5 discusses the composition of a Trend variable which accounts for quality improvements independent of climatic changes that attempts to capture the effect of rating inflation.

4.5 Dependent Variable: Wine Price

An alternative measure of wine quality is the price paid for a bottle or case of wine. Such a dataset could be comprised of retail or auction price data, both with advantages and disadvantages. Retail data is a broader representation of wines across recent vintages and captures first release prices from primary sales. This allows comparison of mainstream wines across vintages per label, with stable, market-related prices set by merchants. Many high-end wines are not on offer in retail, so while representation of mainstream wines is thorough, price data for scarce labels and vintages is thin. Another problem encountered is that retail prices don’t necessarily reflect sales. Merchants could be holding over-priced stock which garners little demand, in which case price is less relevant. Auction prices however reflect actual transactions. They have less representation of wines than retail price data, as they contain price data mostly of flagship wines from prestigious vineyards and exceptional vintages. According to Wood and Anderson (2006:6), “Auction prices provide a comparatively high degree of price transparency, and therefore provide the best indication of the equilibrium value of a particular vintage”. Auctions also attract international buyers and are often a better reflection of global market demand than local retail pricing.

Ashenfelter and Storchmann (2010) find that in the Mosel Valley, temperature has a greater effect on auction prices compared to retail prices, increasing 63% and 37% respectively for every 1°C growing season warming. Therefore, if weather does in fact play a role in wine quality, the effect should be most prevalent in auction prices. Ashenfelter's (2008) famous Bordeaux equation and Byron and Ashenfelter's (1995) Penfold's Grange model were both developed using auction price as the dependent variable.

Europe and America have well-established auction markets presenting the finest and rarest wines. Christies and Sotheby's are the leading institutions, offering online bidding to collectors and investors in search of the best vintages from the likes of Bordeaux, Burgundy, and California. In 2023, Sotheby's held 70 auctions, amassing £160 million in bids across 22,000 lots (Sotheby's, 2023). In South Africa the auction market for fine wines is much thinner. The institution most similar to the likes of Sotheby's is Strauss and Co., who accept bidding on international and local wines on behalf of private clients and organisations. Strauss and Co. run themed auctions throughout the year, like Bordeaux-styled or Rhone-styled wines, with international and local wines on offer.

Constructing a comprehensive dataset from these auction lots presents significant challenges due to the limited representation of vintages for any given wine and the inconsistency in lot sizes. A lot could be a single bottle, three bottles, a six-bottle case, a twelve-bottle case, large-pack bottle sizes, or a mixture of vintages in a case. According to Fox and Melser (2014), lots with greater number of units require price adjustments, further complicating the analysis. Investors are also willing to pay more for complete cases than loose bottles as it provides greater confidence in terms of wine authenticity (Cardebat *et al.*, 2017). Additionally, bottle age, the difference between the auction year and the harvest year, differs greatly and has a major effect on auction prices (Ashenfelter, 2008). Wines can be anywhere from two to fifty years old at auction, adding an additional layer of complexity to the analysis when controlling for the effect of bottle age. Consequently, the resulting dataset is highly unbalanced and poses challenges for statistical analysis.

The best candidate for the construction of a local auction price dataset is the Cape Winemaker's Guild (CWG) Auction. Established in 1982, the CWG is a collective of South Africa's greatest winemakers. Membership to the Guild is by invitation only, with the criteria of producing wine for at least five years that consistently exceeds industry standards (CWG, 2024). Members are expected to demonstrate a commitment to the local wine industry through innovation, development, and sharing of knowledge. Since its inception, only 41 members have been part of this illustrious group.

The 2024 auction was run over two days, raising more than R16 million from almost 300 bidders across 13 countries. In total, 2,118 cases of 6x750ml bottles were sold at an average of R1,309 per bottle, at R1,210 and R1,375 for white and red wines respectively. All 545 lots of 48 wines were sold (CWG, 2024), and annual auction results are published on the CWG website. What makes this data source better is the consistency of wines and winemakers across vintages and the consistency of pack-size; namely 6x750ml bottle cases. The issue of multiple vintages across inconsistent pack-sizes in a single purchase is absent in the CWG auction. As per the criteria used for quality ratings, wines considered must be red Bordeaux-style WO Stellenbosch wines.

The age of the bottle at auction is pertinent and requires discussion. This style of wine is often aged for two years before bottling; hence a lag exists between vintage year and the year in which the wine appears on auction, this difference is called bottle age. Bottle age becomes a critical factor for wines that have been aged for an extended period, after which the bottle's scarcity, maturation, and therefore investment value greatly increases (Jones and Storchmann, 2001). Maturation refers to the development of tertiary aromas and complexity over time which is achieved after several years (30+ years for some Bordeaux wines) of careful cellaring. The bottle age of CWG wines in the dataset are

between two and five years. Approximately 75% of the wine prices are from bids on two- and three-year-old bottles. Over this period, it is assumed bottle age plays a negligible role in terms of maturation, scarcity, and therefore price.

Annually, each wine made for the CWG auction is specifically labelled and created as its own product. Generally, each winemaker will produce less than 100 cases of the CWG wine, with about half going on auction. Some producers might exploit this fact and offer less cases than other winemakers. This induces an element of manufactured scarcity which may play a role in the prices bid. Prices are inflation-adjusted to real terms, with 2022 as the base year, using consumer price indices from the Abstract of Agricultural Statistics (DAFF, 2023).

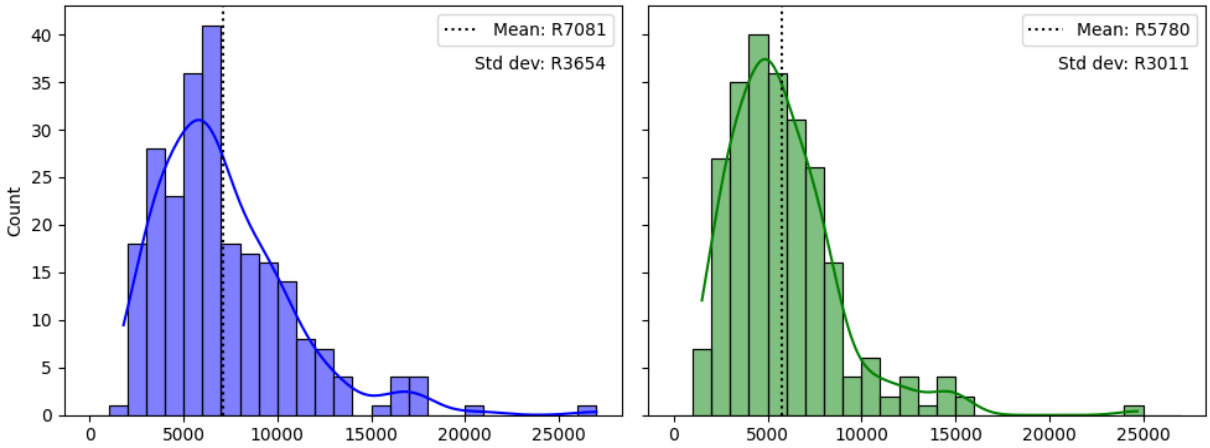


Figure 4.15: Distribution of Cape Winemaker's Guild auction bids in 2022 real prices from 2003-2024 (n=242). Left: Highest bid per case of 6x750ml bottles. Right: Average bid per case of 6x750ml bottles.

The dataset contains 242 observations of Bordeaux-style wines from Stellenbosch, with an average of 11 ratings per vintage from 2001-2021. The same varietal criteria used in the assessment of quality ratings applies: the wine must be made from either a single varietal or blend of Cabernet Sauvignon, Merlot, Cabernet Franc, Petit Verdot, or Malbec. The CWG data contains fields for the "Highest Bid" and "Average Bid" across lots for a wine. The highest bid (Figure 4.15) has a mean of R7,081 per case and a standard deviation of R3,654, compared to R5,780 per case and a standard deviation of R3,011 for the average bid across lots, implying the highest bid is expectedly larger with more variability.

For the portfolio of wines analysed, the Kanonkop Paul Sauer Bordeaux blend accounts for nine of the ten most expensive bottles (Appendix K). The most expensive being the 2015 vintage which had an average selling price of R24,700 per case, a staggering R4,100 per bottle. This was perhaps fuelled by the 100-point score it achieved from notable international wine critic Tim Atkin MW - a first for South African wine. The average bid price is preferred over the highest bid price which could prove too volatile. A single bad actor, like the owner of a wine estate, can ruin the highest price metric by simply bidding an unreasonable amount of money for their auction lot, whereas the average price is a better reflection of demand across multiple lots.

The relationship between average and highest bid prices per year is shown in Figure 4.16. The highest bid increases at 6% per year, while the average bid increases by 5% per year. The price growth represents real, inflation-adjusted value appreciation. This could be due to the prestige that CWG wines has gained, rising global interest in South African wines, or improved quality due to advanced farming and winemaking practices resulting in better wines.

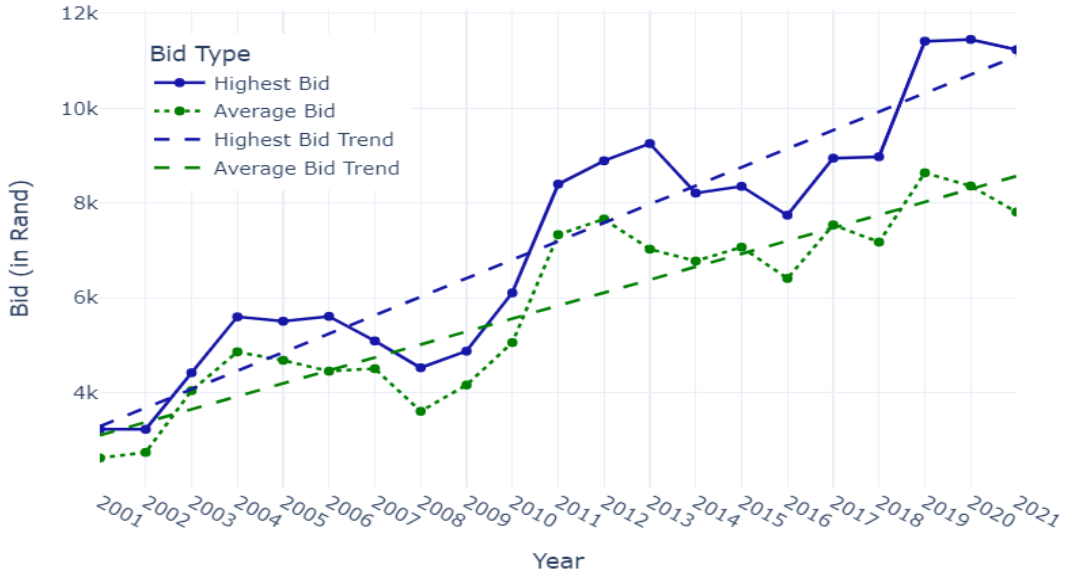


Figure 4.16: Annual CWG auction bids per 6x750ml case (inflation adjusted, 2022 real prices).

In their analysis of fine wine pricing across auction venues, Oleksy *et al.* (2021) find that wine quality, proxied by Robert Parker ratings aggregated at a regional level, are positively and significantly related to fine wine auction prices. Ashenfelter (2008) and Vittorio and Ginsburgh (1996) both conclude that Bordeaux wine prices achieved at auction serve as highly reliable indicators of wine quality. Similarly, the relationship is evaluated for the CWG wines and the wines whose quality ratings are assessed. Figure 4.17 plots the natural logarithm of average bid prices on the left axis and quality ratings per vintage on the right axis. They are strong, positively correlated (r=0.78) and statistically significant with $p < 0.001$.

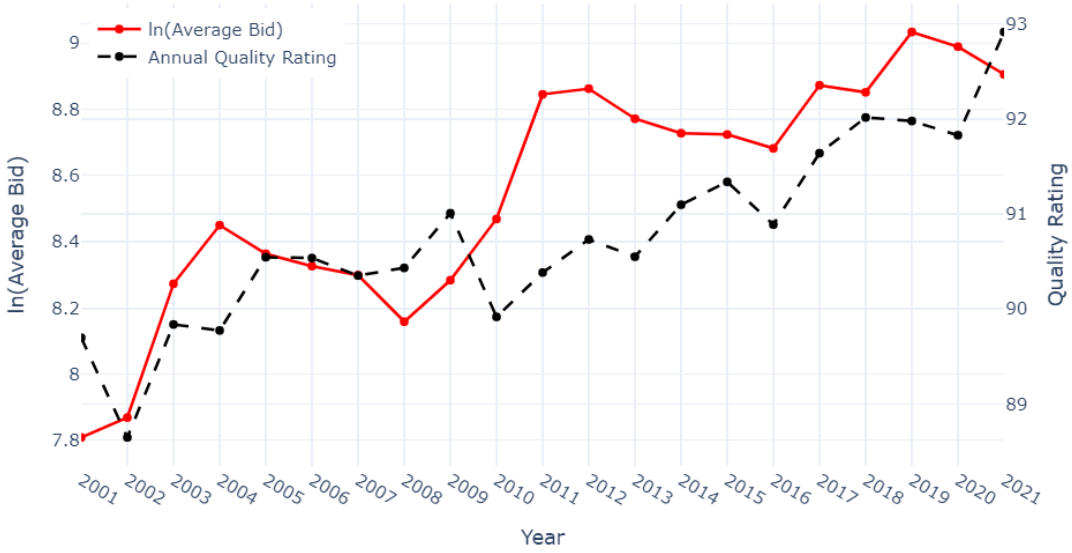


Figure 4.17: Relationship between the natural logarithm of CWG auction prices and annual quality ratings.

Auction prices tend to have a skewed distribution, as evidenced in Figure 4.15. They also tend to contain outliers, like outstanding vintages from famous vineyards (e.g. Kanonkop CWG Paul Sauer 2015). The natural logarithm (ln) compresses these extreme values, making it closer to a normal distribution and thus improving the validity of the linear regression assumptions. In a log-linear model, correlation coefficients are interpreted as percentage effects, rather than absolute changes (Appendix L).

5. Results and Discussion

5.1 Weather and Wine Quality Ratings

Regression results assessing the effect of climate variables on wine quality ratings out of 100 points from 2001-2021 is presented in Table 5.1. The dependent variable is the averaged wine rating score for a vintage across a portfolio of 33 red Bordeaux-style Stellenbosch wines. Twelve models are constructed, and the coefficients are estimated with statistical significance reported, along with the standard errors, adjusted R-squared, Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). An intercept is fitted but not reported.

Growing Season Average Temperature (GSAT) is calculated as the average daily temperature from the start of October to the end of March in degrees centigrade. Harvest Rain refers to the total rainfall recorded throughout January and February in millimetres. Winter Rain is the summation of rainfall from April to September in the year preceding the harvest. The Growing Season Diurnal Temperature (GSDT) variable represents the average daily difference between maximum and minimum temperatures from October to March. GSDT and a squared harvest rainfall term are insignificant across all models tested (Appendix J).

Across all models, winter rainfall is shown to have no effect on quality ratings. A similar investigation of the effect of weather on quality ratings of the Australian Penfolds Grange wine, also finds winter rainfall to be insignificant (Byron and Ashenfelter, 1995). This is contrary to the findings of Ashenfelter, Ashmore and Lalonde (1995) who concluded that winter rainfall has a significant positive effect on wine prices in Bordeaux.

This discrepancy may stem from systemic differences in viticultural practices and environmental conditions between Bordeaux, Stellenbosch, and Australia. European viticulture imposes rules relating to planting of cultivars, winemaking practices, and irrigation. This is especially true under the strict French *appellation d'origine contrôlée* (AOC) system (France, 2006). The vast majority of French vineyards are not irrigated (Ashenfelter and Storchmann, 2016), compelling vines to rely on deep-rooted access to groundwater reserves built up during the winter. Australia and South Africa being part of the New World wine producing regions have far more flexibility in terms of irrigation practices. This may account for the insignificance of winter rainfall affecting quality ratings. New World producers can mitigate seasonal water deficits through both groundwater reserves and supplementary irrigation during dry conditions (Gladstones, 2011).

The baseline model (1) indicates that GSAT is significant with a positive coefficient, meaning warmer growing temperatures result in better wine ratings. GSAT alone explains 26% of the variation in wine ratings. The addition of the squared GSAT term (2) renders both variables insignificant, subsequently decreasing their explanatory power compared to the baseline model. With the addition of the rainfall variables (3) and (4), only harvest rainfall bears significance ($p = 0.080$).

The portfolio of wine experienced rating inflation at approximately 0.14 points per year (model 5). This could be due to improvements in farming practices, winemaking technology, labour relations, mechanization, marketing, or other factors not captured by weather variables.

Table 5.1: Regression results of wine quality ratings and weather, 2001-2021 (n=21).

	Model 1		Model 2		Model 3		Model 4	
Variable	coef	P-Value	coef	P-Value	coef	P-Value	coef	P-Value
GSAT	0.606** (0.21)	0.010	4.911 (9.97)	0.628	9.566 (9.68)	0.337	9.333 (9.70)	0.350
$GSAT^2$			-0.107 (0.25)	0.671	-0.222 (0.24)	0.368	-0.216 (0.24)	0.383
Harvest Rain					-0.010* (0.01)	0.080	-0.012* (0.01)	0.056
Winter Rain							0.001 (0.00)	0.347
Adj. R-squared	0.265		0.232		0.325		0.322	
AIC	53.8		55.6		53.7		54.5	
BIC	55.9		58.7		57.9		59.7	

Table 5.2: Regression results of wine quality ratings and weather including the Trend variable, 2001-2021 (n=21).

	Model 5		Model 6		Model 7		Model 8	
Variable	coef	P-Value	coef	P-Value	coef	P-Value	coef	P-Value
Trend	0.140*** (0.02)	0.000	0.130*** (0.02)	0.000	0.131*** (0.02)	0.000	0.124*** (0.02)	0.000
GSAT			0.145 (0.13)	0.278	6.697 (5.08)	0.205	9.589* (4.61)	0.054
$GSAT^2$					-0.163 (0.13)	0.214	-0.234* (0.11)	0.058
Harvest Rain							-0.006** (0.00)	0.025
Adj. R-squared	0.791		0.794		0.801		0.847	
AIC	27.4		28.0		28.0		23.2	
BIC	29.5		31.1		32.2		28.4	

Significance at the 10%, 5%, and 1% levels are indicated as *, **, *** respectively.
Std errors are shown in parentheses.

The international perception is that South Africa has only produced high-quality wine for a short period, if at all. As such, farmers, viticulturists, and winemakers have more to learn compared to Old World producers. They are required to constantly adapt their practices to optimize the cultivar-vineyard relationship to produce the best wine. It could also be due to wine critics becoming more generous awarding high scores. Jones *et al.* (2005) refer to it as "a time-correlated bias of critics".

Jones *et al.* (2005) create a "Trend" variable which accounts for quality improvements independent of climatic changes, assigned a value of 1 in 2001, incremented by a value of 1 annually until 2021. The Trend variable aims to capture technological improvements and the effect of higher critic ratings. The inclusion of the Trend variable significantly improves the previously tested models (Table 5.2). The Trend variable is highly significant ($p < 0.001$) with a positive coefficient, confirming the presence of rating inflation. Trend alone accounts for almost 80% of the variation in wine ratings. The expectation therefore is that each subsequent vintage should be better than the preceding ones.

Model 8 is the best performing, with both the linear and quadratic GSAT terms marginally significant, harvest rainfall significant ($p = 0.025$) with a negative coefficient, and Trend remaining highly significant ($p < 0.001$). Model 8 confirms that rating inflation exists. The negative harvest rainfall coefficient indicates that any precipitation in January and February is detrimental to the vineyard, in agreement with existing literature (e.g. Ashenfelter, Ashmore and Lalonde, 1995; Byron and Ashenfelter, 1995; Oczkowski, 2016; Davis *et al.*, 2019; Ramirez, 2008). The negative squared growing temperature coefficient is an indication that warming is beneficial, but beyond a certain point becomes detrimental. It follows that an optimal growing season temperature which maximizes wine quality ratings must exist.

5.2 Estimating Optimal Growing Season Average Temperature

The optimal growing season temperature can be found using the same procedure as Jones *et al.* (2005) and Oczkowski (2016). To determine the optimal GSAT ($GSAT_{opt}$), find the partial derivative of the best performing regression model (Model 8) with respect to temperature and set to zero:

$$\text{Rating} = \beta_0 + \beta_1\text{Trend} + \beta_2\text{GSAT} + \beta_3\text{GSAT}^2 + \beta_4\text{HarvestRain}$$

$$\frac{\partial \text{Rating}}{\partial \text{GSAT}} = \beta_2 + 2\beta_3\text{GSAT}_{opt} = 0$$

Solving for $GSAT_{opt}$:

$$\text{GSAT}_{opt} = -(\beta_2/2\beta_3) \quad (1)$$

Substituting the value of coefficients: $\beta_2 = 9.589$, $\beta_3 = -0.234$ into (1):

$$\text{GSAT}_{opt} = -(9.589 / [2*(-0.234)])$$

$$\text{GSAT}_{opt} = \underline{20.5°C}$$

According to the best-performing linear regression model, the growing season temperature that optimises wine quality ratings is 20.5°C. The growing season temperature ranges in Figure 5.1 are derived based on the climatic and phenological requirements in the world's *benchmark* regions for each variety. The optimum ranges are not rigid, however changes of +/- 0.2°C-0.6°C are highly unlikely (Jones, 2006). The theoretical upper GSAT limit of Cabernet Franc, Merlot, and Malbec is 19°C, and 20°C for Cabernet Sauvignon (Figure 5.1). If we assume that the upper limit of mentioned varietals can increase by 0.6°C (Jones, 2006), then the absolute maximum GSAT for Cabernet Franc, Merlot, and Malbec becomes 19.6°C, and 20.6°C for Cabernet Sauvignon.

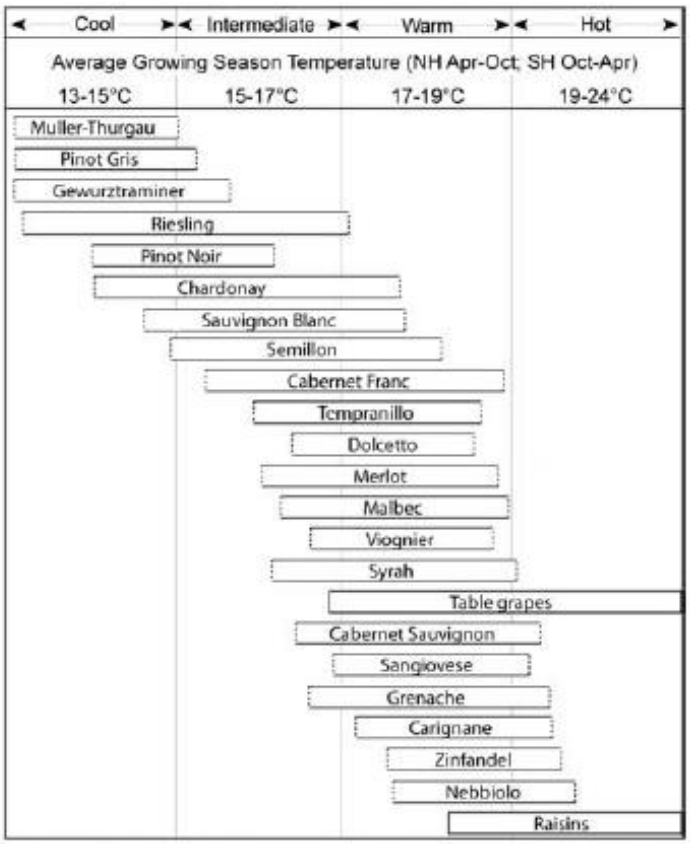


Figure 5.1: Grapevine climate and maturity groupings for wine production amongst popular cultivars (Source: Jones, 2006).

A reasonable conclusion would be that once the Stellenbosch GSAT exceeds the estimated optimum of 20.5°C, the quality of grapes used in a Bordeaux blend would start to diminish, as the non-Cabernet grapes would be pushed well past their theoretical heat limits. However, upon inspecting the above average vintages since 2001 (Figure 5.2), all nine vintages had a GSAT between 20.5°C and 21.7°C, with the stellar 2009 vintage experiencing a GSAT of 21.4°C. The equally memorable 2015 vintage had a GSAT of 21°C, both vintages experiencing growing season temperatures above the theoretical upper limit. This brings into question the validity of the upper bounds of Figure 5.1. One can argue that the first growth wines of Bordeaux are in a different league to the best wines in Stellenbosch, however, local winemakers have shown that 95+ point wines can successfully be made under much warmer conditions than theorised.

Van Leeuwen *et al.* (2013:E3051) argues that the temperature range for most varietals may be wider than suggested in Figure 5.1. They state that "it is very difficult to establish precise upper limits by variety for growing high-quality wines and that those given [in Figure 5.1] are underestimated". Van Leeuwen *et al.* (2013) also strongly oppose the view of Hannah *et al.* (2013) who claim that by 2050 most of the wine-growing regions will become unsuitable for viticulture. Van Leeuwen *et al.* (2013) points out that the Rheingau (Germany), Burgundy (France), and the Rhone Valley (France) are producing high quality wines even though growing season temperatures have already exceeded the upper limits depicted in Figure 5.1. This also seems to be the case for the constituent varietals of Bordeaux blends in Stellenbosch.

The estimated optimal temperatures for Stellenbosch, Australia and Bordeaux from multiple sources are presented in Table 5.3. The estimated optimum value calculated for Stellenbosch is 3.1°C higher than the $GSAT_{opt}$ calculated for Bordeaux by Jones *et al.* (2005).

Table 5.3: Optimal GSAT for Bordeaux blends and cultivars across different regions.

Region	**Cultivar**	**Optimal Temp.**	**Ref.**
Stellenbosch	Bordeaux Blend	20.5°C	
Australia	Cabernet Sauvignon	18.5°C	1
Australia	Cabernet Sauvignon	18.6°C	2
Australia	Merlot	17.5°C	2
Bordeaux (France)	Bordeaux Blend	17.4°C	3

Adapted from: 1. Webb *et al.* (2008), 2. Byron and Ashenfelter (1995), 3. Jones *et al.* (2005)

5.3 Weather and Wine Auction Prices

The regression results of weather and its effect on inflation-adjusted auction prices are presented in Table 5.4. The same explanatory variables are used as in the regression of weather and wine quality ratings. The best wine quality rating model (Model 8) is included for comparison. The Trend variable is highly significant ($p < 0.001$) and positive across all three models, indicating that both auction prices and wine critic scores of WO Stellenbosch Bordeaux blends are increasing over time. Model 13 suggests that each year we can expect inflation adjusted auction prices to increase by 5.1%. The price growth represents real, inflation-adjusted value appreciation. This could be due to the prestige that CWG wines has gained, rising global interest in South African wines, or improved farming and winemaking practices. The temperature and rainfall variables are statistically significant in the quality ratings model, but not the auction price models. Therefore, while climate impacts quality assessments, they do not translate directly to auction price movements.

Table 5.4: Regression results of wine auction prices and weather including the Trend variable, compared to the best quality rating model (Model 8), 2001-2021 (n=21).

	Model 13 ln(Auction prices)		Model 14 ln(Auction prices)		Model 8 Quality ratings	
Variable	coef	P-Value	coef	P-Value	coef	P-Value
Trend	0.051*** (0.01)	0.000	0.057*** (0.01)	0.000	0.124*** (0.02)	0.000
GSAT			1.565 (1.94)	0.431	9.589* (4.61)	0.054
$GSAT^2$			-0.041 (0.05)	0.409	-0.234* (0.11)	0.058
Harvest Rain			-0.001 (0.00)	0.528	-0.006** (0.00)	0.025
Adj. R-squared	0.790		0.799		0.847	
AIC	-14.58		-13.14		23.2	
BIC	-12.49		-7.92		28.4	

Significance at the 10%, 5%, and 1% levels are indicated as *, **, ***.
Std errors are shown in parentheses.

In the quality ratings dataset, a proportion of critics have tasted the wines *blind*, while others have not. It is not possible to quantify the actual number of blind scores as the WineSearcher scores are pooled from multiple critics, many of which do not declare the type of tasting. However, the Wine Spectator component of the scores is blind tasted. Auction prices are distinctly different as they are not blind and therefore influenced by additional factors such as market sentiment, winemaker reputation, collector behaviour, and tasting notes or quality ratings from critics. It follows that quality ratings might influence auction prices, as informed buyers will have access to this information.

Models 15 and 16 include critic ratings to assess their effect on auction prices compared to the Trend variable (Table 5.5). Quality ratings alone (Model 15) exhibit a positive and highly significant ($p < 0.001$) relationship with auction prices. The model suggests that a 1-point increase in wine rating results in a 28.7% increase in auction price. However, the inclusion of Trend alongside quality ratings (Model 16) causes the coefficient for ratings to become insignificant. It was previously demonstrated that ratings and auction prices are strongly correlated (Figure 4.17), suggesting that the long-term trend in prices already captures much of the variation explained by critic ratings. While critic ratings appear to influence prices, their effect is largely absorbed by broader market trends over time.

Table 5.5: Regression results of wine auction prices, critic ratings, and the Trend variable for 2001-2021 vintages (n=21).

	Model 15 ln(Auction prices)		Model 16 ln(Auction prices)	
Variable	coef	P-Value	coef	P-Value
Trend			0.056*** (0.01)	0.001
Ratings	0.287*** (0.05)	0.000	-0.036 (0.09)	0.680
Adj. R-squared	0.590		0.780	
AIC	-0.56		-12.78	
BIC	1.53		-9.64	

Significance at the 10%, 5%, and 1% levels are indicated as *, **, ***.
Std errors are shown in parentheses.

Factors independent of weather and wine quality could also affect consumer appetite at an auction. For instance, the 2024 CWG auction marked the first release from Christo le Riche, son of legendary winemaker Ettienne le Riche, the first Pinot Noir on auction from Richard Kershaw, and the final Kanonkop Paul Sauer and Pinotage wines produced by Abrie Beeslaar (CWG, 2024). These debut and final releases carry unique historical and sentimental significance, potentially increasing their value beyond intrinsic wine quality. This highlights the role of external factors unrelated to weather conditions or wine quality, like scarcity, producer reputation, and collector interest in shaping auction outcomes.

5.4 Future Vintage Predictions

Using the quality ratings model (Model 8), we predict the vintage rating for the years 2022, 2023, and 2024 which were omitted from the analysis due to lack of available ratings. The main reason why ratings don't exist for recent vintages is the lag effect induced by ageing. Top-class Bordeaux-style wines are often aged for 12-24 months in oak barrels. The ageing process allows the wine to integrate flavours, developing complexity and aroma. Even after bottling, there might still be a delay before ratings are published, as the wines need to be sent for tasting and are added to the backlog of wines at ratings agencies. The predictions for future vintages are shown in Table 5.6. The model estimates that they will be very close in terms of quality, with 2023 slightly below 2024 and 2022 due to increased harvest rainfall and lower growing season temperatures.

Table 5.6: Predicted Vintage Ratings of 2022, 2023, 2024.

Vintage	GSAT	HR	Rating
2022	20.784°C	16.80 mm	92.48
2023	20.110°C	49.95 mm	92.37
2024	20.775°C	39.60 mm	92.58

To evaluate the model predictions, vintage quality ratings are compared to the qualitative feedback contained in the annual South African Wine Harvest Reports prepared by Vinpro. These reports provide an analysis of the national harvest, as well as findings from the district level. The reports for the 2022, 2023, and 2024 harvests are summarized in Appendix M.

The ranking, though not explicitly stated, suggests that 2024 stands out as the best vintage among the three, followed by 2022 and 2023. The model's predictions align with this order of vintage quality - 2024: 92.58, 2022: 92.48, 2023: 92.37).

5.5 A climate-based vintage quality heuristic

After calculating the average vintage score for the twenty-year period (90.77/100 points), a label of "Above Average" or "Below Average" is allocated to each vintage. Plotting vintage label on a chart of GSAT vs harvest rainfall, we obtain Figure 5.2 which allows one to visually determine how vintages fit together in terms of their rating, GSAT, and harvest rainfall. Ashenfelter (2008) states that warm, dry summers result in great Bordeaux wines. It is therefore reasonable to expect that Stellenbosch's vintages should cluster in a similar manner, i.e. above average vintages should be found in the quadrant with low rainfall and warmer temperatures.

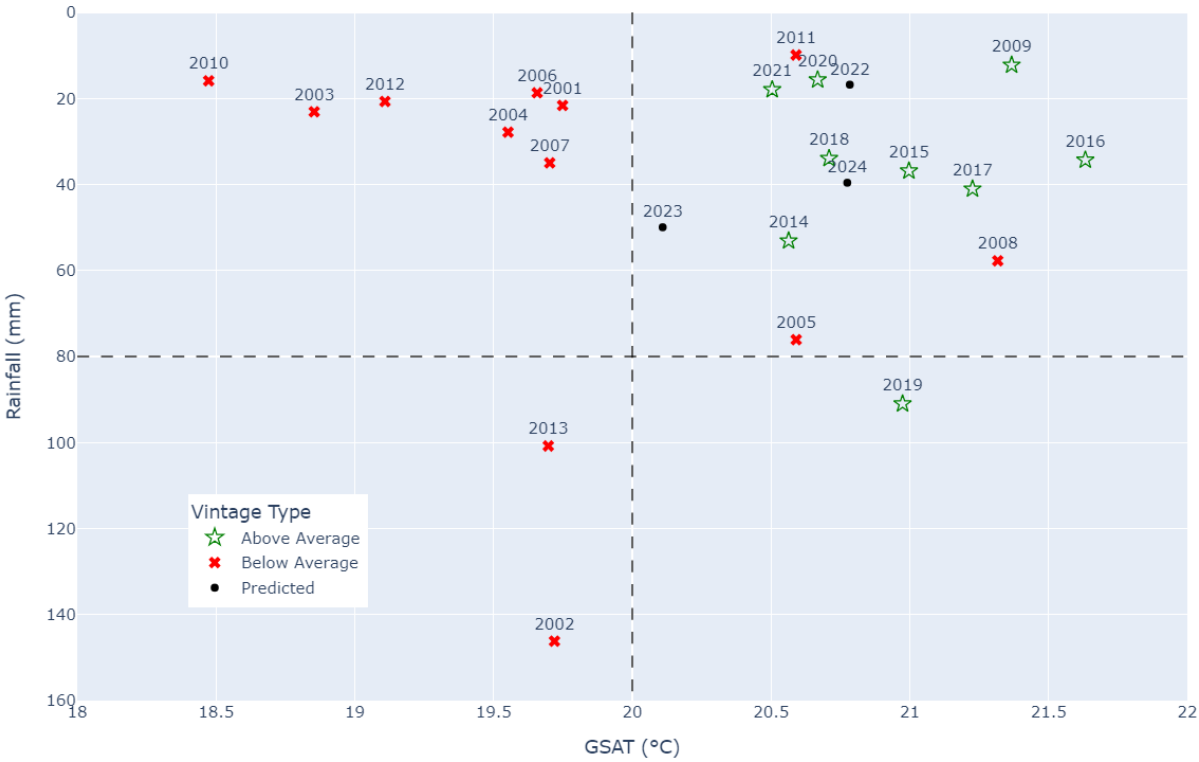


Figure 5.2: Each vintage's GSAT and harvest rainfall, marked by either a cross or a star if it was a below or above-average vintage. The unrated 2022, 2023, and 2024 vintages are marked with black dots.

Above-average vintages indeed cluster at the top right of the graph. That is, warmer growing seasons with little harvest rainfall produce better wines. The 2024 and 2022 vintages fit within this cluster, while the slightly lesser 2023 vintage lies on the outskirts. Note the universally acclaimed 2009 vintage in the furthest top right-hand corner. Figure 5.2 suggests a heuristic whereby vintages with harvest rainfall below 60 mm and GSAT above from 20.5°C onwards are likely to be very good vintages. This agrees with the findings of Ashenfelter (2008) whose above average vintages cluster in the same fashion (Figure 5.3).

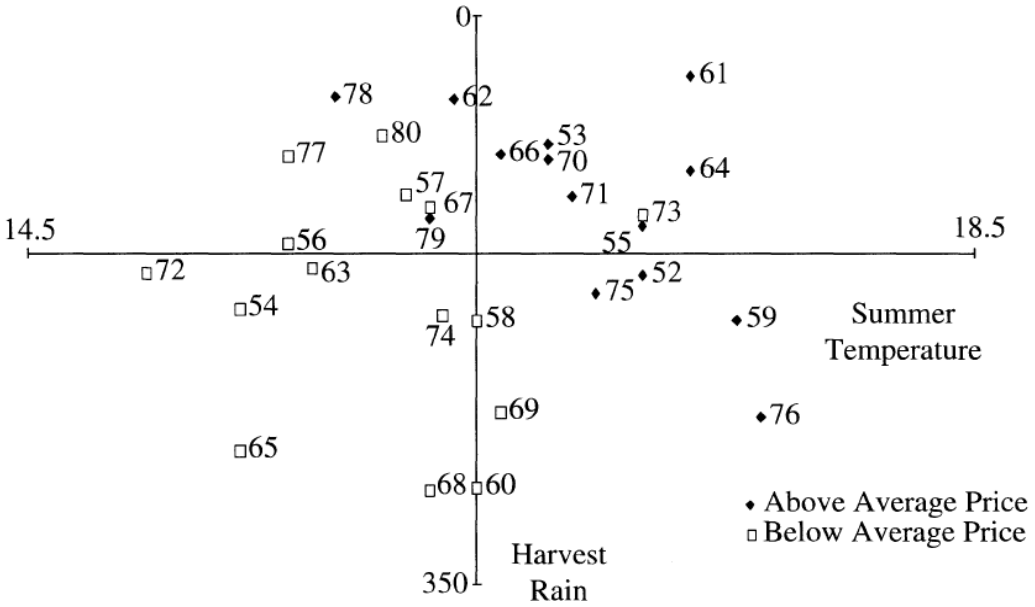


Figure 5.3: Above and Below-Average Bordeaux vintages in terms of their summer temperature and harvest rainfall, 1952-1980 (Source: Ashenfelter, 2008).

An anomaly in Bordeaux is the 1973 vintage. It falls in the correct quadrant based on Ashenfelter's heuristic but achieves a below-average price on the auction market. According to Ashenfelter, wines from this vintage are above average quality but have always sold at lower prices. He states, "insiders know they are often bargains" (Ashenfelter, 2008). Employing a similar approach for the Stellenbosch vintages, Figure 5.2 suggests that the below average rated vintages of 2008 and 2011 might prove to be the best value for money wines compared to other vintages on sale.

To quantify the similarity between vintages in terms of harvest rainfall and growing temperatures, we use the Euclidean distance formula as a measure of *closeness*. A preprocessing step is necessary as GSAT and harvest rainfall have different units and scales. To standardize these measures, we apply a min-max scaler, transforming their values to the range [0,1]. The three nearest vintages in terms of GSAT and harvest rainfall are reported in Table 5.7. The Euclidian distance is reported in parentheses, where smaller values mean vintages are more similar. Based on the *similar vintage* heuristic, wine collectors should be excited about the 2024 vintage, which is closely related to the phenomenal and highly sought after 2015 vintage. A similarity matrix for all vintages for the 2001-2021 period is reported in Appendix H.

Table 5.7: The three most similar vintages in terms of GSAT and harvest rainfall. Euclidean distances are reported in parentheses.

Vintage	Nearest Vintage	2nd Nearest Vintage	3rd Nearest Vintage
2024	2018 (0.05)	2015 (0.07)	2014 (0.12)
2023	2014 (0.15)	2007 (0.17)	2018 (0.22)
2022	2020 (0.04)	2011 (0.08)	2021 (0.09)

5.6 Limitations

This study is confined to the wine district of Stellenbosch in the Western Cape of South Africa. The paper focuses on arguably the most renowned cultivar-site combination of high-end South African wine: Bordeaux-style Stellenbosch wines. Based on Figures 2.5 and 5.1, the constituent grapes in a Bordeaux blend, namely Cabernet Sauvignon, Merlot, Cabernet Franc, Malbec, and Petit Verdot have similar temperature maturity profiles. The effect of weather should then reasonably be the same across all five cultivars, minimising the effect of cultivar-specific sensitivities in the analysis. Since the

focus is on flagship wines from each estate, the results are not necessarily representative of entry- or mid-level wines in Stellenbosch, nor the rest of the Western Cape.

Data from two weather stations is utilized: Jonkershoek records daily temperature and rainfall data Stellenbosch records only daily rainfall. These stations are operated by the South African Weather Service and fall within the Stellenbosch wine district. The wine quality ratings dataset represents wines from 20 different estates, each within 22km from the Jonkershoek weather station, at a mean distance of 14km. This approach is in line with Ashenfelter's analysis (2008) where a single station in Merignac was chosen to represent the weather in Bordeaux. Ultimately the objective is to evaluate the temperature experienced by the vines and the subsequent quality of the wine made from the constituent grapes. Unfortunately, the effect of a vineyard's microclimate cannot be captured precisely at this resolution. To fully understand vintage variations at the estate level, vineyard-specific weather records should be used to best capture the climate factors associated with a vineyard's terroir.

In their PhD dissertation, Southey (2017) emphasizes the difficulty in accessing climate data for the Western Cape that is reliable and at a meaningful spatial and temporal level. Midgley *et al.* (2016:69) agrees, stating "a key challenge to understanding the Western Cape climate system and processes is the lack of observations".

The auction price data is much thinner than the wine quality ratings dataset. Over the same period, the Cape Winemakers Guild auction had half the records (n=242) of the critic ratings dataset. This auction dataset is limited in comparison to existing literature like Haeger and Storchmann (2006) who analysed American Pinot Noir prices over a much shorter period from 1998 to 2004 (n=451). The local auction market for wines is far less developed than regions known for producing highly collectable and age-worthy wines like France or Italy, hence the sparseness of data.

The wines analysed do not have a perfect distribution of ratings throughout the analysis period from 2001 to 2021. A longer period of analysis would've been preferable but remains in line with existing literature like Byron and Ashenfelter (1995) (24 years) and Ashenfelter, Ashmore and Lalonde (1995) (28 years). A total of 571 wine bottle ratings makes up the average vintage scores.

Wine quality ratings are widely available from numerous sources, making the selection of appropriate datasets a key consideration. This study employed sources from a free and open-source repository (WineSearcher), and scores from the renowned Wine Spectator publication which is a paid service. Using additional subscription-based data sources was not feasible due to financial constraints. For quality ratings, a criterion for a wine's consideration was that 50% of ratings over the period had to be present. The lowest number of ratings for a wine was 12 out of 20 possible vintage ratings, with an average of 17.3 ratings per wine label. Some labels lack ratings for specific years. This is perhaps due to a bottle belonging to a below average vintage or logistical issues faced in shipping bottles to overseas-based critics. Ideally, each bottle's vintage rating would be analysed, this would ensure consistency in the analysis across labels and vintages. The addition of ratings from critics familiar with South African wine would greatly improve the dataset and therefore robustness and accuracy of results.

6. Conclusion

This study set out to model the effect of key climate variables, including temperature and rainfall, on the quality of Stellenbosch Bordeaux-style red wines, using critic ratings and auction prices as dependent variables over the period 2001-2021. The study further sought to estimate an optimal growing season temperature, develop a climate-based vintage quality heuristic, and evaluate potential rating inflation and price trends over time.

Considerable warming is evident over the last 20 years in Stellenbosch, specifically the last ten years. Summer and winter rainfall appear to have no discernible trend. Growing season conditions, specifically relating to temperature and rainfall, have been shown to affect vine phenology. This in turn affects the grape's sugar, acidity, alcohol levels, and quality in general.

For the portfolio of Stellenbosch Bordeaux blends assessed, a quadratic relationship between growing season temperatures and wine quality ratings exists. Warming during the season is beneficial up to an estimated optimal temperature of 20.5°C, but empirical evidence suggests the true optimum may be higher. Rain during the months of January and February is found to be harmful to the vineyard, while no winter rainfall effect is reported. In Bordeaux, wet winters, warm growing seasons and a dry harvest result in great vintages. Australia has been shown to have a quadratic relationship with growing season temperature and is adversely affected by harvest rainfall with no winter rainfall effect reported. Stellenbosch is therefore more like Australia than Bordeaux in terms of the weather's effect on wine quality.

The climate-based heuristic suggests a growing season with temperatures from 20.5°C and less than 60mm of rain in January and February has an increased chance of being a great vintage. The heuristic suggests that 2008 and 2011 are undervalued vintages, and to expect cellar-worthy 2022 and 2024 vintages. Inflation is evident for quality ratings. Either critics are becoming more generous, or viticultural and winemaking-related practices are improving overall wine quality, or a combination of the two is happening. Similarly, inflation-adjusted auction prices for these wines have increased more than 5% annually. This price growth represents real value appreciation, suggesting that the rating inflation may be attributed to objectively better wines. Weather does not seem to influence auction prices.

Limitations surrounding the availability of spatially and temporally appropriate weather data is discussed. Ideally a greater number of observations would be used for the construction of both the quality measures. The results are confined to the varietals that make up a Bordeaux blend, namely, Cabernet Sauvignon, Merlot, Cabernet Franc, Petit Verdot and Malbec. Future research should aim to use higher resolution weather data, both spatial and temporal, and test the effect on a larger dataset of wine scores. This could include vineyard-specific weather stations tracking live temperature, rainfall, and other climate data. These results could be used to aid winemakers in making decisions regarding cultivar suitability at a specific site. The effect of weather on wine quality should be extended across different varietals and wine districts within the Western Cape.

Literature has shown that global warming will produce winners and losers. Regions currently too cold for viticulture will be able to grow cool climate grapes, while warm regions may be pushed beyond the feasible realm of grape growing. Growing conditions are warmer, and rainfall is becoming more unpredictable in both magnitude and frequency. A warmer future is a drier one, and it would be reasonable to expect a larger incidence of heat waves and droughts. The New World producer's ability to irrigate as required is beneficial in the short run, but future assurance of water for agricultural use is not guaranteed. It is imperative that farmers embrace the adaptation strategies proven to offset the effect of a warmer and drier future. The increase in ratings and auction prices may already reflect these

successful adaptations. Stellenbosch's winemakers have already demonstrated resilience, but increasing water scarcity may alter vineyard management dynamics, potentially making winter rainfall a more significant factor, as observed in Bordeaux. Long-term sustainability will depend on proactive adaptation to evolving climate conditions.

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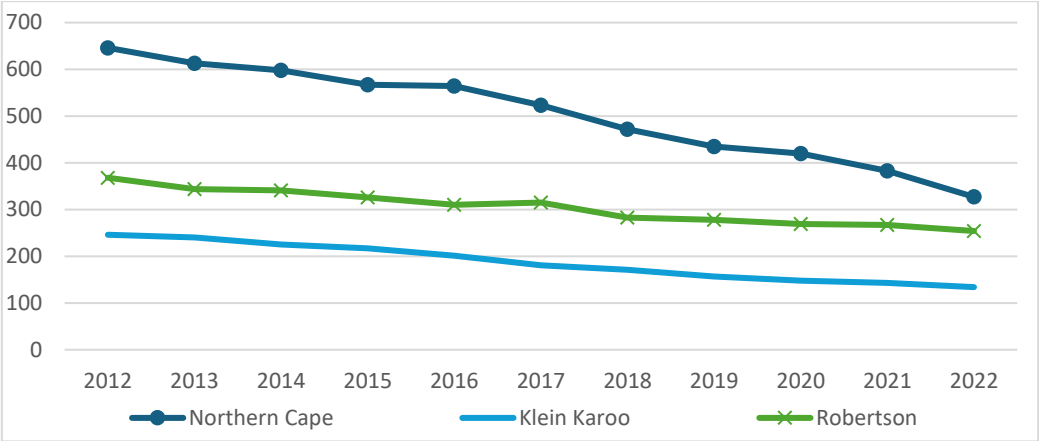
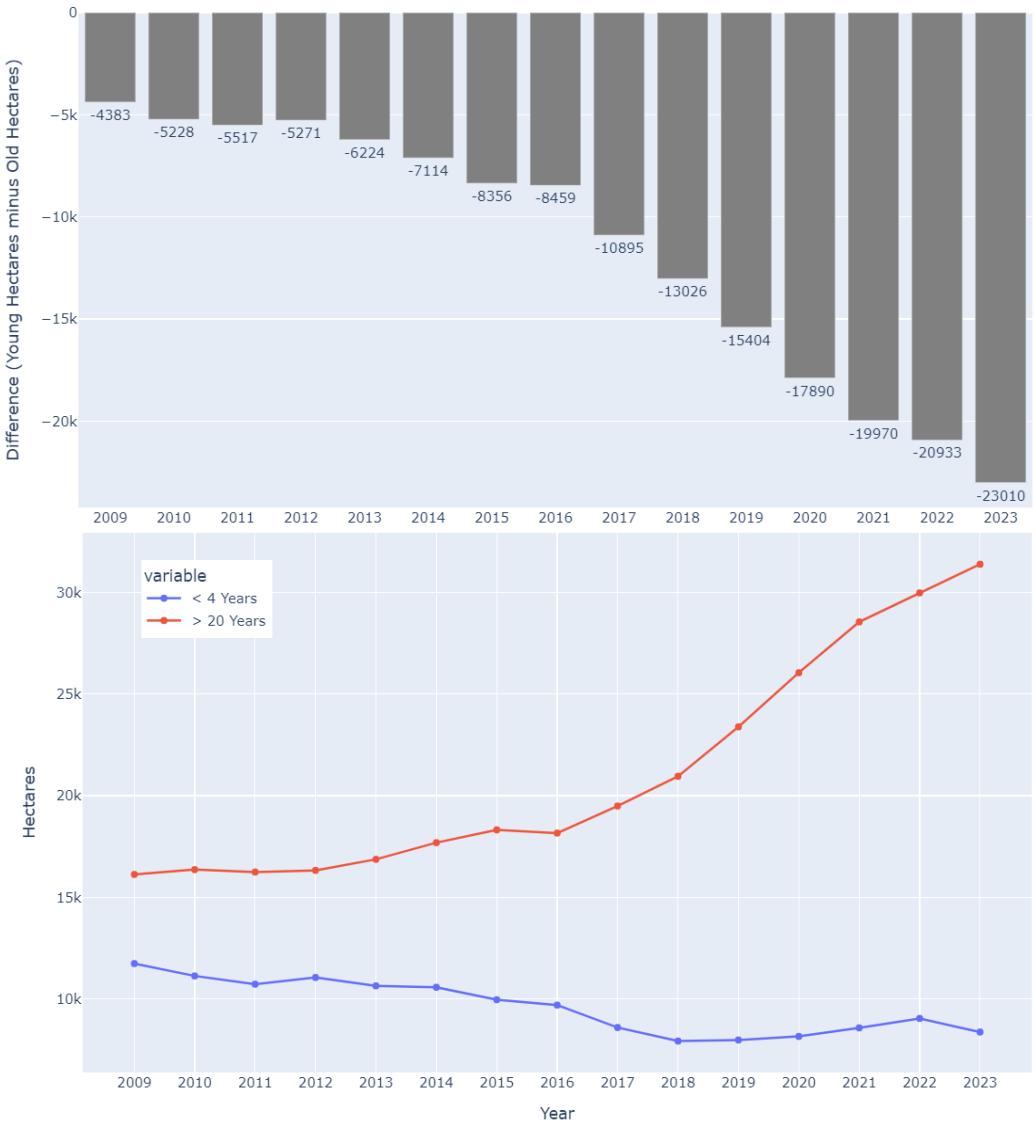
Appendices

Appendix A: The exit of grape producers per selected region (Adapted from: SAWIS, 2024)



Appendix B: Difference between old and young vine hectares across the Western Cape (Adapted from: SAWIS, 2024).



Appendix C: Comparison of Rating Organizations and Wine Critics.

	CellarTracker	Wine Spectator	Wine Searcher	Decanter	James Suckling
Rating Type	User-generated.	Professional panel.	Aggregated results by critics.	Professional panel (MWs).	Professional panel.
Features	Community-driven, transparent.	Blind tastings, highly respected.	Price comparisons.	Expert panels, focus on Old World.	Focus on younger wines.
Strengths	Diverse perspectives.	Consistency, commitment to fair judgement.	Aggregates diverse views, reduces bias.	European wines.	Consumer friendly, all regions represented.
Flaws	Novices record ratings, wines tasted at different ages.	Paid access, mainstream focused.	Mixed sources which could confuse consumers.	Limited New World focus, conservative ratings.	Overly positive ratings, scoring inflation.
Audience	Everyday consumers.	Serious collectors, investors	Price-conscious buyers.	European wine enthusiasts.	Everyday consumers, New World enthusiasts.
SA Wine Coverage	Excellent.	Well represented.	Excellent.	Poor.	Well represented.
Availability	Free.	Paid.	Free.	Paid.	Paid.
Data Used	No.	Yes.	Yes.	No.	No.

Appendix D: Heat summation indices and temperature variables for Stellenbosch.

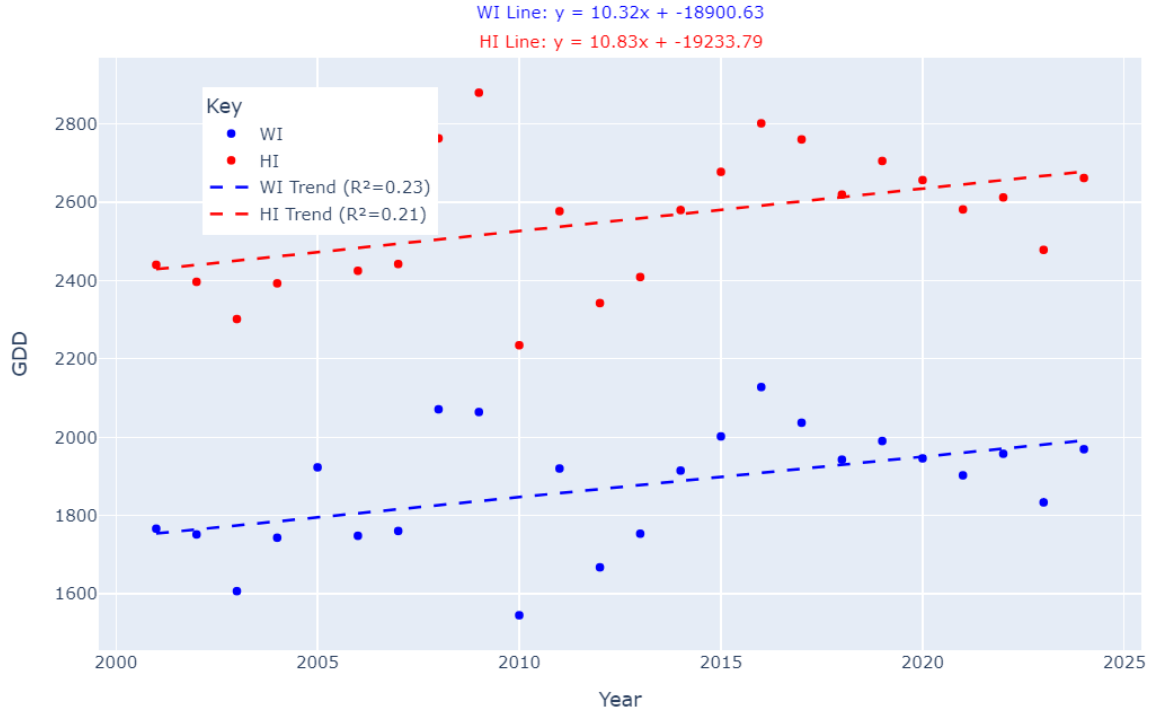


Figure D-1: Winkler Index (WI) and Huglin Index (HI) trends, Stellenbosch (2001-2024).

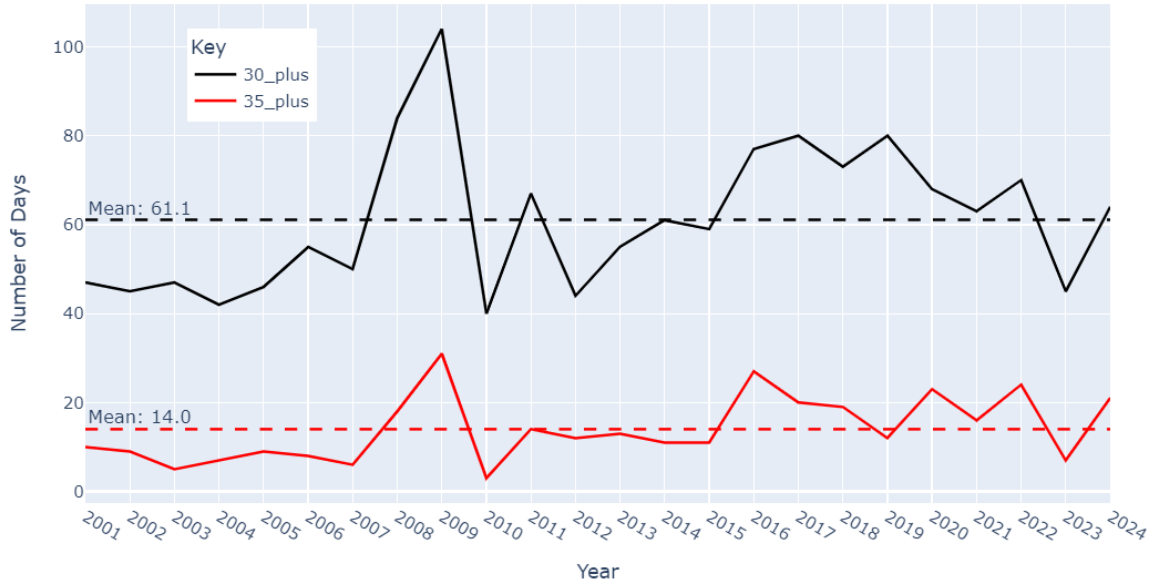
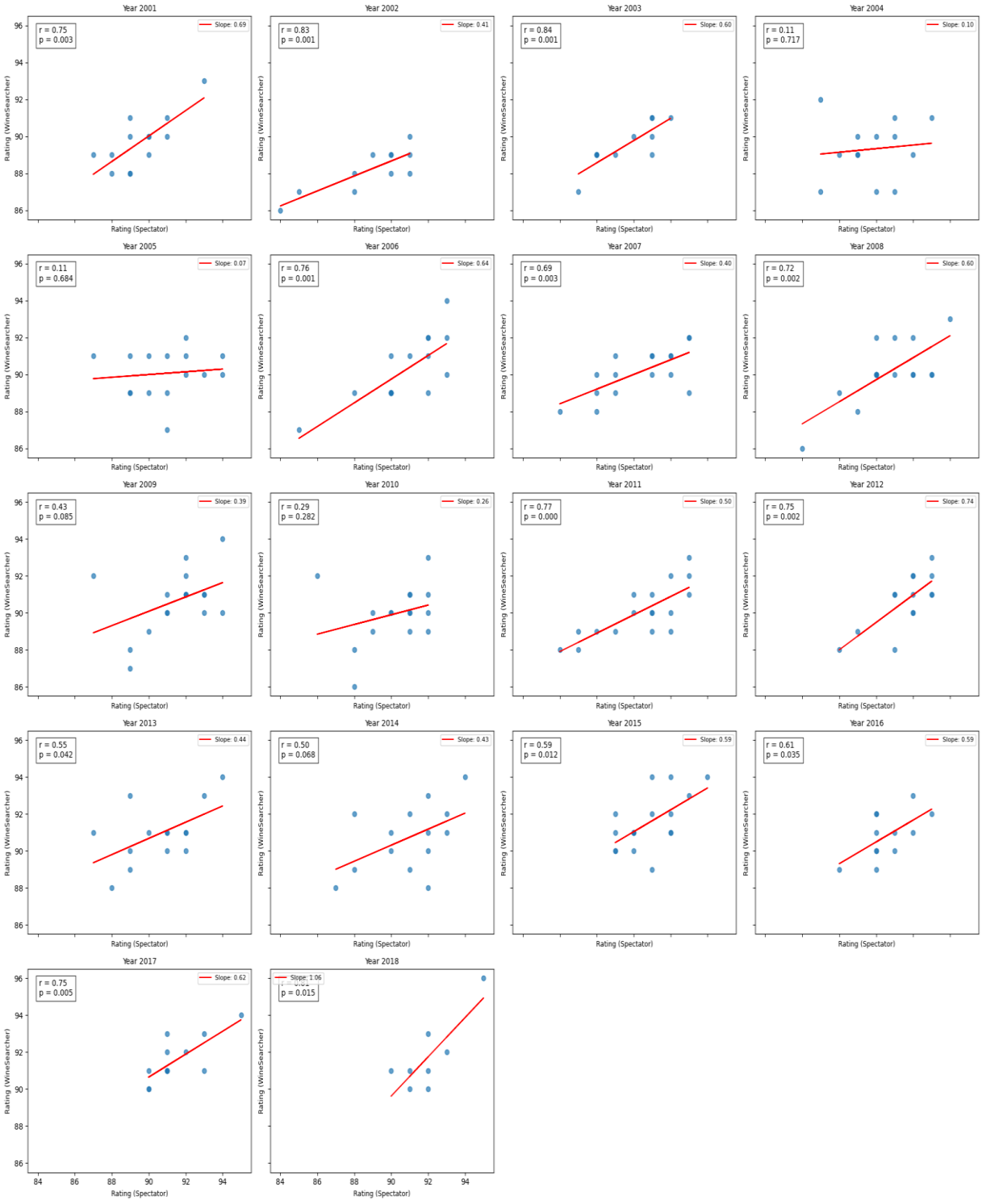


Figure D-2: Number of days above 30°C and 35°C, Stellenbosch (2001-2024).

Appendix E: Count of vintage ratings for the portfolio of 33 wines investigated (mean = 17.3).

Index	Wine Label	Count
1	Raats Family Cabernet Franc	21
2	Rust en Vrede Cabernet Sauvignon	21
3	De Toren Fusion V Bordeaux Blend	20
4	Neil Ellis Cabernet Sauvignon	20
5	Thelema Cabernet Sauvignon	20
6	Kanonkop Paul Sauer Bordeaux Blend	20
7	Thelema Merlot	20
8	De Trafford Cabernet Sauvignon	20
9	Warwick Trilogy Bordeaux Blend	20
10	Rust en Vrede Estate Bordeaux Blend	20
11	Kanonkop Cabernet Sauvignon	19
12	Ernie Els Signature Bordeaux Blend	18
13	Le Riche Reserve Cabernet Sauvignon	18
14	Warwick Estate Cabernet Franc	18
15	Rustenberg Peter Barlow Cabernet Sauvignon	18
16	Vergelegen Reserve Cabernet Sauvignon	17
17	Tokara Director's Reserve Bordeaux Blend	17
18	Vergelegen V Cabernet Sauvignon	17
19	Waterford Estate Cabernet Sauvignon	17
20	Meerlust Rubicon Bordeaux Blend	17
21	Jordan Sophia Bordeaux Blend	17
22	Hartenberg Cabernet Sauvignon	17
23	De Trafford Elevation 393 Bordeaux Blend	17
24	De Toren Z Bordeaux Blend	17
25	Rust en Vrede Merlot	16
26	Raats Family De Compostella Bordeaux Blend	16
27	Simonsig Cabernet Sauvignon	16
28	Hartenberg The Mackenzie Bordeaux Blend	16
29	Miles Mossop Maximillian Bordeaux Blend	15
30	Stark-Conde Three Pines Cabernet Sauvignon	15
31	Boekenhoutskloof Cabernet Sauvignon	15
32	Rust en Vrede 1694 Classification Cab. Sauv.	14
33	Finlayson Edgebaston GS Cabernet Sauvignon	12

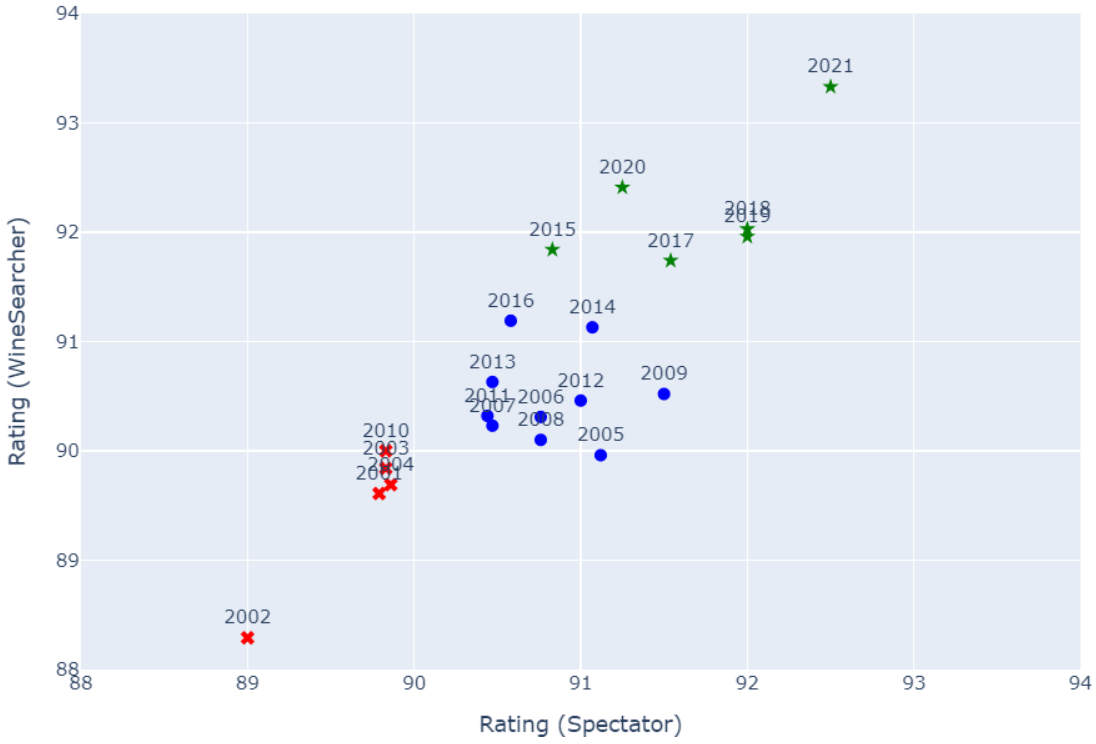
Appendix F-1: Correlation coefficients and p-values between Wine Spectator and WineSearcher ratings. Each data point represents a score for the same bottle of wine by both rating agencies.



Appendix F-2: Pearson correlations of annual Wine Spectator vs WineSearcher ratings for the same bottles of wine (n=18). Bold correlation coefficients indicate p-values < 0.05.

Year	Correlation (r)	p-value	Best Fit Gradient
2001	**0.75**	0.003	0.69
2002	**0.83**	0.001	0.41
2003	**0.84**	0.001	0.60
2004	0.11	0.717	0.10
2005	0.11	0.684	0.07
2006	**0.76**	0.001	0.64
2007	**0.69**	0.003	0.40
2008	**0.72**	0.002	0.60
2009	0.43	0.085	0.39
2010	0.29	0.282	0.26
2011	**0.77**	0.000	0.50
2012	**0.75**	0.002	0.74
2013	**0.55**	0.042	0.44
2014	0.50	0.068	0.43
2015	**0.59**	0.012	0.59
2016	**0.61**	0.035	0.59
2017	**0.75**	0.005	0.62
2018	**0.81**	0.015	1.06

Appendix G-1: Clustering of Stellenbosch vintages from 2001-2021 based on the respective ratings with labels Top (star), Mid (circle), and Bottom-tier (cross), outliers (2002 and 2021) included.



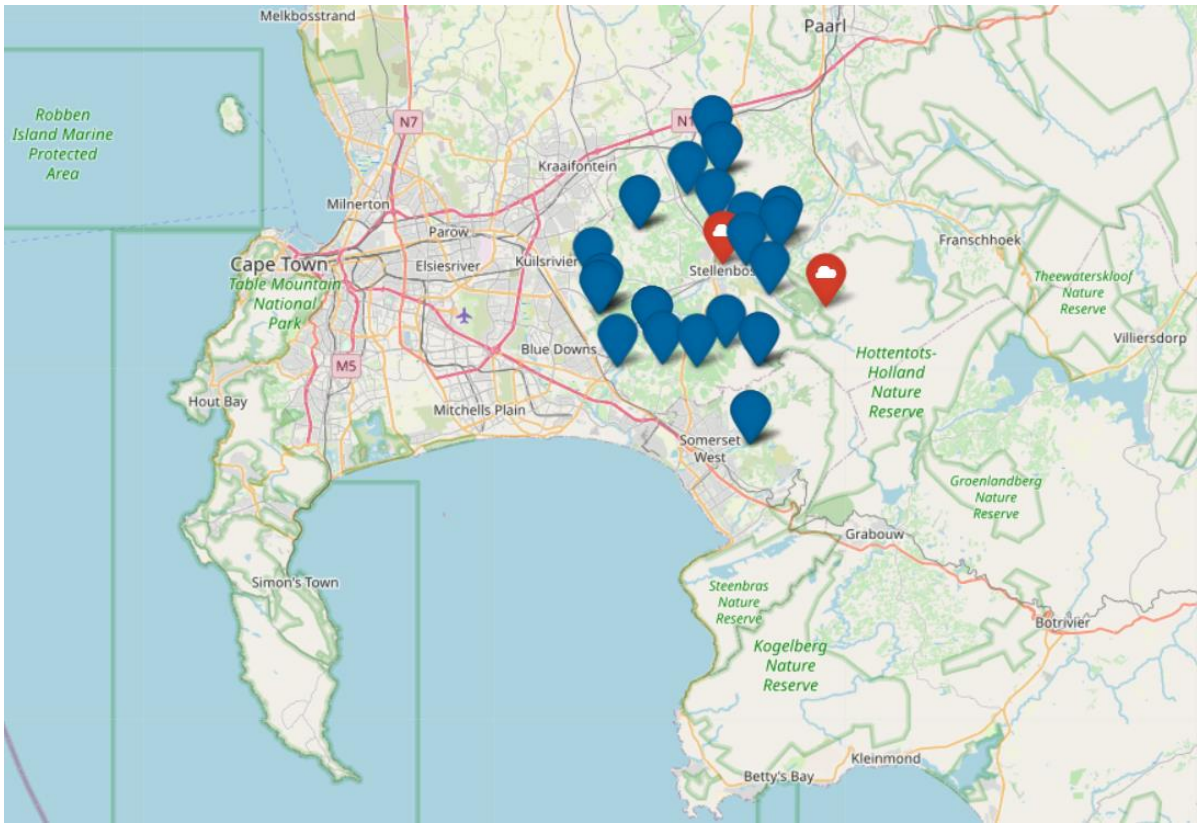
Appendix G-2: Clustering of Stellenbosch vintages from 2001-2021 based on the respective ratings. Labels are assigned after conducting K-means clustering with n=3.

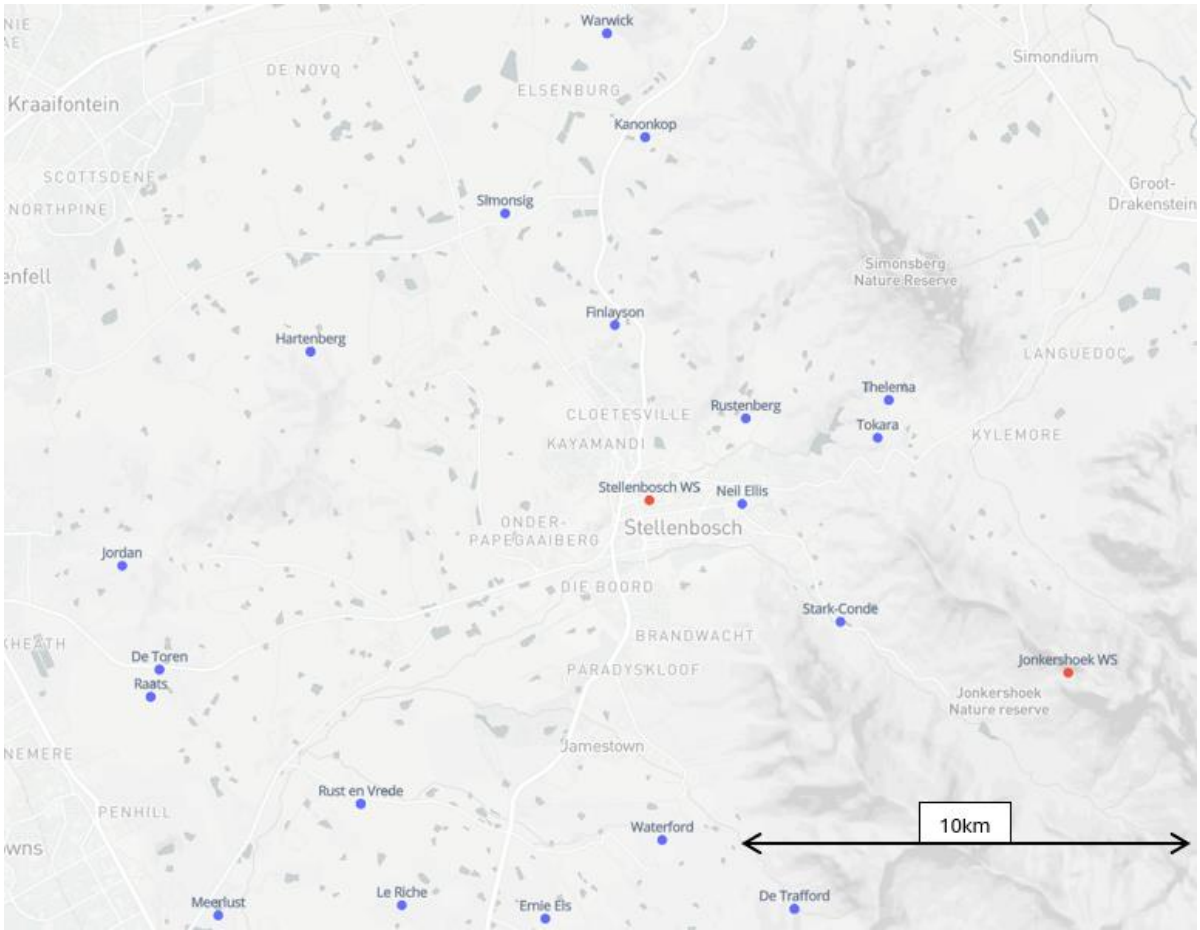
Vintage	Rating (Spectator)	Rating (WineSearcher)	Cluster
2001	89.79	89.61	Bottom-Tier
2002	89	88.29	Outlier, Removed
2003	89.83	89.84	Bottom-Tier
2004	89.86	89.69	Bottom-Tier
2005	91.12	89.96	Mid-Tier
2006	90.76	90.31	Mid-Tier
2007	90.47	90.23	Mid-Tier
2008	90.76	90.1	Mid-Tier
2009	91.5	90.52	Mid-Tier
2010	89.83	90	Bottom-Tier
2011	90.44	90.32	Mid-Tier
2012	91	90.46	Mid-Tier
2013	90.47	90.63	Mid-Tier
2014	91.07	91.13	Mid-Tier
2015	90.83	91.84	Top-Tier
2016	90.58	91.19	Mid-Tier
2017	91.54	91.74	Top-Tier
2018	92	92.03	Top-Tier
2019	92	91.96	Top-Tier
2020	91.25	92.41	Top-Tier
2021	92.5	93.33	Outlier, Removed

Appendix H: The most similar vintages in terms of GSAT and harvest rainfall. Euclidean distances are reported in parentheses, smaller values indicate closer groupings.

Vintage	Nearest Vintage	2nd Nearest Vintage	3rd Nearest Vintage
2024	2018 (0.05)	2015 (0.07)	2014 (0.12)
2023	2014 (0.15)	2007 (0.17)	2018 (0.22)
2022	2020 (0.04)	2011 (0.08)	2021 (0.09)
2021	2020 (0.05)	2011 (0.07)	2022 (0.09)
2020	2022 (0.04)	2011 (0.05)	2021 (0.05)
2019	2005 (0.16)	2008 (0.27)	2014 (0.31)
2018	2024 (0.05)	2015 (0.09)	2022 (0.13)
2017	2015 (0.08)	2008 (0.13)	2016 (0.14)
2016	2017 (0.14)	2009 (0.18)	2008 (0.20)
2015	2024 (0.07)	2017 (0.08)	2018 (0.09)
2014	2024 (0.12)	2023 (0.15)	2018 (0.15)
2013	2002 (0.33)	2005 (0.34)	2023 (0.40)
2012	2003 (0.08)	2004 (0.15)	2006 (0.17)
2011	2020 (0.05)	2021 (0.07)	2022 (0.08)
2010	2003 (0.13)	2012 (0.20)	2004 (0.35)
2009	2016 (0.18)	2022 (0.19)	2015 (0.22)
2008	2017 (0.13)	2015 (0.18)	2016 (0.20)
2007	2004 (0.07)	2001 (0.10)	2006 (0.12)
2006	2001 (0.04)	2004 (0.07)	2007 (0.12)
2005	2019 (0.16)	2014 (0.17)	2023 (0.24)
2004	2007 (0.07)	2006 (0.07)	2001 (0.08)
2003	2012 (0.08)	2010 (0.13)	2004 (0.22)
2002	2013 (0.33)	2019 (0.57)	2005 (0.58)
2001	2006 (0.04)	2004 (0.08)	2007 (0.10)

Appendix I: Locations of estates included in the ratings dataset; maps are north facing. Estates have blue markers, weather stations are marked in red.





Appendix J: Regression results of GSDT and Harvest Rainfall squared on wine quality ratings.

	Model 9			Model 10		
	coef	std err	P-Value	coef	std err	P-Value
Trend	0.124***	0.02	0.000			
GSAT	11.850**	5.09	0.035	10.608	10.84	0.343
GSAT_squared	-0.291**	0.13	0.038	-0.249	0.27	0.372
Harvest Rain	-0.005	0.00	0.102	-0.011	0.01	0.106
Winter Rain	0.000	0.00	0.892	0.001	0.00	0.472
GSDT	0.158	0.14	0.265	0.088	0.29	0.767
Adj. R-squared	0.842			0.281		
AIC	25.1			56.4		
BIC	32.4			62.6		

Significance at the 10%, 5%, and 1% levels are indicated as *, **, *** respectively (n=21).

	Model 11			Model 12		
	coef	std err	P-Value	coef	std err	P-Value
Trend				0.121	0.02	0.000
GSAT	9.946	9.58	0.315	9.832**	4.39	0.041
$GSAT^2$	-0.234	0.24	0.341	-0.241**	0.11	0.043
Harvest Rain	0.012	0.02	0.542	0.008	0.01	0.403
Harvest $Rain^2$	0.000	0.00	0.257	0.000	0.00	0.123
Adj. R-squared	0.339			0.861		
AIC	53.9			21.8		
BIC	59.2			28.0		

Significance at the 10%, 5%, and 1% levels are indicated as *, **, *** respectively (n=21).

Appendix K: Top 20 most expensive wine by Cape Winemaker's Guild (CWG) average auction bid (inflation adjusted, 2022 real prices) of WO Stellenbosch Red Bordeaux-style wines only (single varietal or blend of Cabernet Sauvignon, Merlot, Cabernet Franc, Malbec, Petit Verdot).

Rank	Auction Year	Wine Label	Vintage	Average Bid
1	2018	Kanonkop CWG Paul Sauer	2015	R24,700
2	2024	Kanonkop CWG Paul Sauer	2021	R15,400
3	2020	Kanonkop CWG Paul Sauer	2017	R15,200
4	2023	Kanonkop CWG Paul Sauer	2020	R14,800
5	2022	Kanonkop CWG Paul Sauer	2019	R14,700
6	2016	Kanonkop CWG Paul Sauer	2013	R14,500
7	2015	Kanonkop CWG Paul Sauer	2012	R14,200
8	2019	Kanonkop CWG Paul Sauer	2016	R13,300
9	2021	Kanonkop CWG Paul Sauer	2018	R12,800
10	2020	Rust en Vrede CWG Auction Estate	2017	R12,200
11	2015	Rust en Vrede CWG Auction Estate	2012	R12,200
12	2016	Hartenberg CWG Auction Cabernet Sauvignon	2014	R12,000
13	2014	Kanonkop CWG Paul Sauer	2011	R11,800
14	2018	Le Riche CWG Auction Cabernet Sauvignon	2015	R11,100
15	2015	Le Riche CWG Auction Cabernet Sauvignon	2011	R10,900
16	2016	Rust en Vrede CWG Auction Estate	2013	R10,700
17	2023	Jordan CWG Sophia	2021	R10,400
18	2023	Miles Mossop Wines CWG Maximilian	2020	R10,200
19	2024	Le Riche CWG Auction Cabernet Sauvignon	2020	R10,200
20	2017	Kanonkop CWG Paul Sauer	2014	R10,200

Appendix L: Interpreting the log-linear specification of Trend in wine auction prices.

The following regression model evaluates the effect of time, represented by the Trend variable, on the inflation-adjusted CWG auction prices:

$$\ln(auction\ price)_T = \beta_0 + \beta_1.Trend \quad (1)$$

where:

- $auction\ price_T$ represents the inflation-adjusted auction price in year *T,*
- β_0 is the intercept,
- β_1 is the estimated coefficient for the $Trend$ variable, capturing the annual percentage change in auction prices.

From (1), auction price at time *T* is expressed as:

$$e^{\ln(auction\ price)_T} = e^{(\beta_0 + \beta_1.Trend)}$$

$$auction\ price_T = e^{\beta_0}.e^{\beta_1.Trend}$$

Similarly, the auction price at time *T* +1*:*

$$\ln(auction\ price)_{T+1} = \beta_0 + \beta_1.(Trend + 1)$$

$$e^{\ln(auction\ price)_{T+1}} = e^{(\beta_0 + \beta_1.(Trend+1))}$$

$$auction\ price_{T+1} = e^{\beta_0 + \beta_1.Trend + \beta_1}$$

$$auction\ price_{T+1} = e^{\beta_0}.e^{\beta_1.Trend}.e^{\beta_1}$$

The year-on-year annual ratio of auction prices is expressed as:

$$\frac{auction\ price_{T+1}}{auction\ price_T} = \frac{e^{\beta_0}.e^{\beta_1.Trend}.e^{\beta_1}}{e^{\beta_0}.e^{\beta_1.Trend}} = e^{\beta_1} \quad (2)$$

Using the estimated Trend coefficient: $\beta_1 = 0.051\ into\ (2)\ yields$

$$\frac{auction\ price_{T+1}}{auction\ price_T} = e^{0.051} = 1.052 = 5.2\%$$

The model therefore suggests an annual percentage increase in inflation-adjusted auction prices of 5.2% for a case of WO Stellenbosch, red Bordeaux-style wines for 2001-2021 vintages.

Appendix M: Summary of Vinpro harvest reports for the 2022-2024 Stellenbosch vintages.

The 2022 growing season was characterized by a delay in vine phenology, with growth stages lagging long-term averages by up to two weeks. January saw extreme heat, with nearly three times the number of hours above 35°C compared to 2021, which significantly impacted vine canopies and delayed ripening. Despite the cool and wet conditions preceding harvest, the extended growing season, large canopies, and dry ripening period resulted in high water consumption. Yields were higher than in 2021, likely due to productive early ripening cultivars, excellent winter cold that improved fertility, and sufficient water availability during berry growth. Later-ripening cultivars benefited from moderate temperatures, achieving full ripeness at optimal sugar and alcohol levels. The region anticipates another classic Stellenbosch vintage, particularly for Cabernet Sauvignon (Vinpro, 2022).

The 2023 season began with promising winter rainfall in May and June. However, rainfall from July to November was below average, although groundwater reserves remained sufficient for healthy vineyard growth. Thunderstorms in December brought significant disease pressure, requiring rapid intervention by producers. Veraison occurred earlier than in 2022, but cool ripening conditions slowed the season's progression. From late February to the end of March, persistent rainfall and cool conditions created major challenges for producers, particularly in optimizing harvest timing. Late-ripening cultivars, including Cabernet Sauvignon, experienced a decline in yields due to issues with berry set following lush growth and losses from Botrytis. Despite these challenges, winemakers noted that phenolic development was sufficiently advanced, resulting in wines with good structure and elegance (Vinpro, 2023).

The 2024 season began with widespread and above-average rainfall in June, replenishing groundwater levels, with flooding experienced in certain areas. Warmer maximum temperatures in August stimulated early cultivar budding. Rainfall was largely absent from September to mid-February, resulting in dry conditions that facilitated steady vine growth. November, January, and February experienced hot weather with daytime temperatures exceeding 35°C, leading to an early harvest, approximately 14 days ahead of schedule. The combination of prolonged dry and hot conditions placed substantial pressure on irrigation infrastructure, particularly affecting dryland vineyards and farms with limited water resources. On the positive side, the dry conditions led to a low incidence of pests and fungal diseases. Producers were particularly impressed with the quality of red wines, and superb wines from the 2024 vintage are anticipated (Vinpro, 2024).

Appendix N: Grapevine growth stages – modified E-L system (Source: Coombe, 1995).