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Impact of Drought on Grape Yields in the Western Cape, South Africa

Masters Dissertation
By
Julio Araujo
ARJJUL001

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Supervisor: Dr Babatunde Abiodun
Co Supervisor: Dr Olivier Crespo

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Abstract

Droughts remain a threat to grape yields in South Africa. Previous studies on the impact of climate variability on grape yield in South Africa have focussed on either the rainfall or the impact of temperature on the grape yields; meanwhile, the grape yields may be more influenced by impacts of drought (which is function of water balance) than that of rainfall or temperature. This study investigates the impact of drought on grape yields in the Western Cape. A drought index that is based on water balance (called, Standardized Precipitation Evapotranspiration Index; hereafter SPEI) was used to analyse drought events at both farm and district scale (Robertson, Olifants River and Stellenbosch districts). Correlation analysis was used to identify the association between drought and grape yield. In addition, the performance of a grape yield model (Agricultural Production Systems sIMulator, APSIM) in simulating the grape yield at farm scale and investigating the sensitivity of yields to drought, with and without irrigation was evaluated.

The results show that, in the past three decades, a series of moderate and severe drought episodes have occurred over the Western Cape at farm and district scales. The severe droughts occur when rainfall is below normal and temperature is above normal, simultaneously. ENSO appears to be an important driver of the severity of drought events in the Western Cape, because most severe droughts occur in El Niño years, while the wet conditions occur in La Niña years. At farm scale, the impact of drought on yields is a significant issue, because in most cases, poor grape yields coincide with at least moderate drought while good yield performance is associated with at least moderate wet conditions; the correlation between drought index and grape yield can be as high as -0.9. However, at district scale, the impact of drought is not a major issue, because the correlation between drought index and grape yield is weak (r = -0.5). This suggests that that most farms are able to mitigate the negative impacts of drought through irrigation management. The APSIM model, which gives a reliable simulation of grape yield at farm scale and shows that without irrigation management, the simulated yields become very sensitive to spring and summer droughts, but less sensitive to autumn and winter droughts.

The study suggest that, in Western Cape, grape yields may be less sensitive to drought at district level because most farmers use irrigation methods that are able to mitigate the impact of climate variability on the yields. Hence, availability of dam and river water for irrigating grapevine is critical for reducing the impact of drought on wine grape yields in future.

Dedication

This Thesis is dedicated to my parents, Carlos Araujo and Liz Van Huyssteen

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- के माध्यम से अपनी थीसिस बाहर मक्खन चिकन के अपने निरंतर आपूर्ति के लिए भारत में खाद्य के लिए धन्यवाद

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Chapter 1: Introduction

1.1 Background

Grapes are fruity berries produced by deciduous woody vines and are generally used for eating and juice production (table grapes) or wine and brandy making (wine grapes). The main difference between table grapes and wine grapes is their composition and planting style. Wine grapes are small, have many seeds, and have thick skin and high sugar content. Alternatively, table grapes are large; often have few to no seeds, thin skin and lower sugar content. The high sugar content in wine grapes, around 22 % – 30 % sugar in comparison to 10 % – 15 % in table grapes, is necessary for fermentation, which gives wine its alcohol content. The treatment of wine and table grapes also differs, as they use different trellis systems (Fig 1.1). Wine grapes use a vertical trellis system that allows the farmer to manage vigour and exposure of grapes to the sun. Table grapes use a "T-shaped" trellis system that allows the grape bunches to hang freely and not to come into contact with one another, the vine or the leaves. Ultimately, table grapes are grown to look and taste good, thus any contact with the grape bunches, which could tarnish the look of the grapes, is managed (Puckette, 2012).

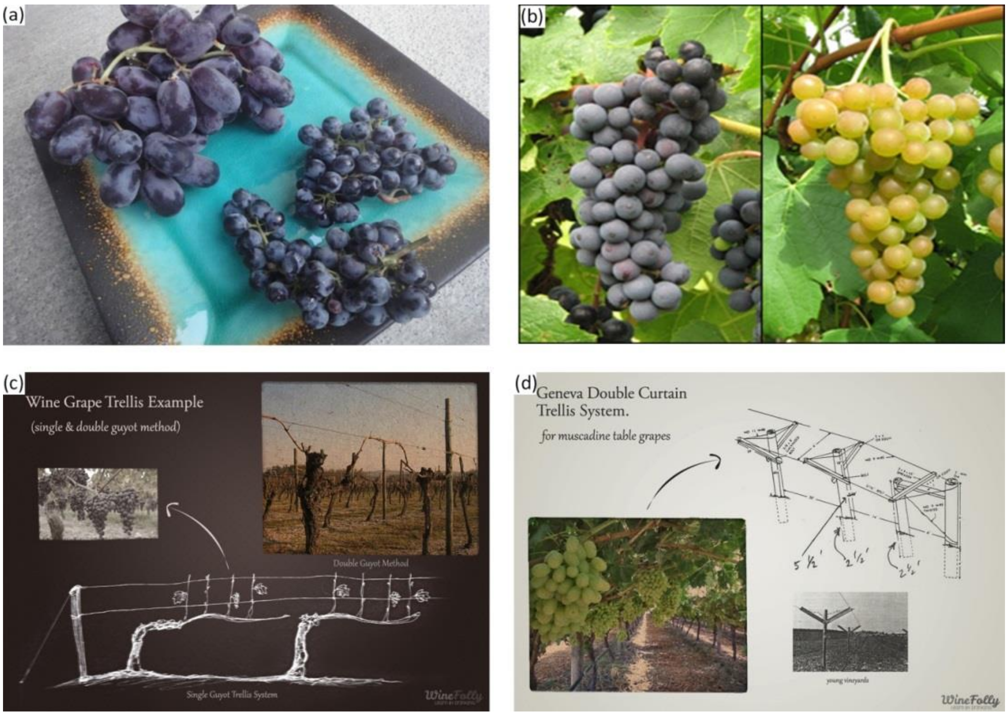

Figure 1.1. Comparison of table and wine grapes. Panel (a) Table (left) and wine (right) grape size comparison, Panel (b) red and white wine grape comparison, panel (c) wine grape trellis system and panel (d) table grape trellis system (Puckette, 2012).

Wine grapes are grown all over the world, where quantity and quality are largely influenced by macro-, meso- and micro-climatic conditions (Spellman, 1999). As such, the wine-growing areas tend to be focussed in Mediterranean type climates and are generally concentrated on similar latitude in the northern and southern hemispheres (Fig 1.2).

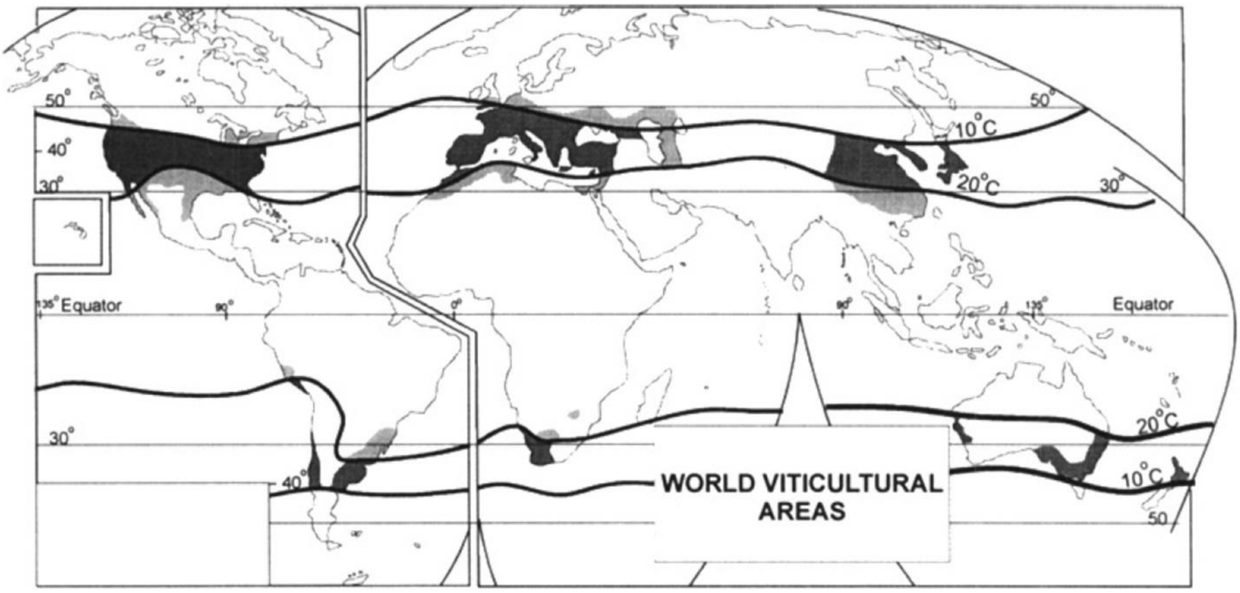

Figure 1.2. Global wine growing areas, thick lines show the 10 °C and 20 °C isotherms (Spellman, 1999).

1.2 Characteristics of South African grapevines

South African winelands consist of a large number of grape varieties, in which the ratio between planted red and white varieties has changed significantly during the past decade. All South African grapes originate from the *Vitis vinifera* species which were imported from Europe. Six of the most common wine grapes grown in the Western Cape are discussed below.

Ruby Cabernet

Ruby Cabernet is a cross between Cabernet Sauvignon and Carignan and is often used for a blending wine. This is a high-yielding grape that tends to perform well in warm climates. It was created to take advantage of the strength and quality of Cabernet Sauvignon with the resistance to rot and heat of the Carignan (WineSA, n.d.).

Merlot

Merlot is a popular red wine in South Africa and has been used for blends and single varietal wines. Merlot, which originates from Bordeaux, tends to be a low-yielding cultivar. This early ripening cultivar performs well in cool, dry climates where there are clay soils. Late season water stress is important for quality Merlot; therefore the soils need to be well drained following rainfall or irrigation (Clarke, 2001). Although Merlot prefers cool climates, it is still susceptible to frost and some fungal diseases.

Shiraz

Shiraz, also known as Syrah in some countries, is a red wine and the grape is able to produce a decent-sized yield. Although Shiraz can be a productive grapevine, the highest quality is often produced with lower yields. The performance of the grapevine is often greater in warmer climates, as it requires hot days to become ripe. The resistance of Shiraz to most pests and diseases allows the grapevine to be planted extensively throughout the Western Cape. It is, however, susceptible to “coulure”, which is a failure of grape development after flowering as a result of climatic conditions (WineSA, n.d.). This grape is extremely sensitive to soil type, thus it is often planted in rich soils, which may add to the flavour of the wine.

Sauvignon Blanc

Sauvignon Blanc is one of South Africa’s most widely planted white grapevines, even though it is a relatively low-yielding grapevine (Goussard, 2008). The performance of Sauvignon Blanc is often affected by diseases. This cultivar prefers cool climates and is often affected by powdery mildew and black rot when there is higher humidity (LaMar, 2005). The location of many Sauvignon Blanc vineyards in Constantia allows the grapevine to perform well as a result of the cooling sea-breeze from the Atlantic Ocean.

Chardonnay

Chardonnay is a relatively low-yielding white grapevine that performs well in both warm and cooler climates (Goussard, 2008). Although Chardonnay performs well in cool weather, it is still susceptible to frost events. This grapevine buds early, which is one of the key reasons for its sensitivity to frost. Chardonnay is one of the most widely consumed wines in the world, which can be attributed to its subtle flavours.

Colombar

Colombar is one of the most resilient white wine grapes planted in South Africa, as it is not susceptible to any major pests or diseases (Robinson, 1986). This grapevine performs well in warm to temperate climates and is sensitive to frost events (Goussard, 2008). Colombar is a high yielding grapevine that tends to ripen late in the season. Although Colombar was initially used for making Cognac, it has now become an integral part of South African wine blends.

1.3 Importance of wine grape production in Western South Africa

It is clear that the wine industry in the Western Cape is a vital aspect of financial and job contributions in both the province and country. Optimal conditions and high standards make South Africa the world's twelfth largest wine producer, accounting for 3.6 % of global production (DAFF, 2012). Like all top wine producing areas, a large portion of wine (bottled and packaged) from the Western Cape is exported around the world. Exports to countries within the European Union account for the bulk of South African exports at 77 %, while North America and Australia account for 8 % and 6 % respectively (DAFF, 2012). Within the country, the Western Cape contains the bulk of South African wineries, accounting for 90.5 % of total production. High global rankings and production result in the Western Cape being a vital part of the agricultural output in the country. Agriculture is a significant contributor to the Western Cape economy, also contributing some 14 % of the national Gross Domestic Product (GDP) and 23 % of the value added of the agriculture sector in South Africa (Vink and Tregurtha, 2010). Similarly, Western Cape grape production contributes more than 50 % of the GDP generated by the wine industry in South Africa (SAWIS, 2010). Not only does the wine industry contribute economically, it also provides a significant portion of valuable jobs in the province. As such, the wine industry accounts for 8 % of employment in the Western Cape (SAWIS, 2010). The Cape Winelands region alone contributes 46 013 full-time employees and 66 883 seasonal employees (Murray, 2011).

The wine industry has been steadily growing, with gross income increasing by 8.4 % from 2011/12 to 2012/13 (DAFF, 2013). This increase means that there is a potential for a larger contribution towards the provincial and national GDP, as well as an increase in jobs. In a country where the availability of jobs is relatively low, it is important that industries such as the wine industry remain productive, so as to ensure the security of jobs, as well as provide additional jobs for both permanent and seasonal workers. Any changes in the productivity of the wine industry, therefore, could reduce the contribution to GDP as well as available jobs. The productivity of the wine industry is reliant on the quality and quantity of both grapes supplied to the cellars and wine exported by the cellars. As such, a change in yield and/or quality may have a negative effect on the wine industry in the Western Cape, which in turn will influence GDP and availability of jobs. There are many external influences that may affect yield, climate and more importantly drought, being the most important.

1.4 Drought in Western South Africa

Drought is a regular and recurring event that has economic, social and environmental implications for South Africa (Rouault and Richard, 2003). It is defined by the Intergovernmental Panel on Climate Change (IPCC) as a prolonged absence or deficiency of rainfall that results in a water shortage for some activity or group (IPCC-AR4, 2007). There are four main forms of drought which are specific to a particular group or sector, such as: "socio-economic drought" which refers to the impact of drought on human activities, "meteorological drought" which refers to a sustained lack of rainfall within a region, "hydrological drought" which refers to a lack in normal water flow and ground water levels that causes a hydrological imbalance, and "agricultural drought" which refers to a water deficit in the top layers of the soil and links meteorological to agricultural impacts (IPCC-AR4, 2007). All forms of drought in South Africa are caused by the high variability in temperature and rainfall (Tyson and Preston-Whyte, 2000). This means that drought is associated with high temperatures as well as accompanying low rainfall; however, the severity of the drought is dependent on the extent of the anomalous changes in each variable.

Some of the variability in South African rainfall can be attributed to the El Niño Southern Oscillation (ENSO) (Meque and Abiodun, 2014). ENSO is the interaction of the global atmosphere with the Pacific Ocean, which results in variability in many ocean and climate patterns (Holloway *et al.*, 2012). The events in the South Pacific Ocean influence the temperature, wind, pressure and rainfall over South Africa. This is such that 30 % of rainfall variability is accounted for by El Niño events (Tyson and Preston-Whyte, 2000). There are two phases associated with ENSO, the cold and warm phases, associate with La Niña and El Niño respectively. El Niño (La Niña) events have a significant impact on winter rainfall in western South Africa, as they are associated with a decrease (increase) in rainfall (Philippon *et al.*, 2011). The warm phase (El Niño) of ENSO is associated with atmospheric convergence occurring off-shore, and thus the uplift which is associated with rainfall is shifted away from the landmass. This shift forces the high-rainfall cloud bands away from the land, resulting in deficit rainfall in those areas and thus providing the conditions for drought to occur (Tyson and Preston-Whyte, 2000). As a result, the warm phase ENSO events have been associated with drought over South Africa, as evidenced in particular, by the severe drought of 2009/10 (Dufois and Rouault, 2012). The drought occurrences (partly forced by ENSO) will have an influence on agriculture in the Western Cape as agricultural drought will influence the available soil water for crops, which may in turn influence the production of wine grapes in the Western Cape. This means that drought events may have a negative impact on grape production in western South Africa.

1.5 Managing Drought

The effect of drought events on grapevine development and yield can be explained by the impact on water status (Van Leeuwen *et al*., 2004). This is such that drought reduces the available water/soil moisture for the vines, which in turn may hinder development and reduce yield (Spellman, 1999). In order to counteract the loss of soil moisture owing to a drought event, supplementary irrigation is needed. The majority of South African vineyards are irrigated which means they have the ability to mitigate the effects of drought. Depending on farm location, the water available for irrigation may vary; for instance, farms near large dams or perennial rivers will have a constant supply of water. Vineyards that are located away from major water sources have to rely on boreholes and private dams to ensure irrigation over a season. These smaller dams are more susceptible to drought, as they have a much smaller holding capacity and are shallow; thus high evaporation along with the normal irrigation schedule will significantly lower water levels in drought years. Between 2000 and 2010 the Garden Route Dam and Gamka Dam’s water storage capacities have steadily decreased (approximately 80 % – 40 % and 80 % – 50 %, respectively (Holloway *et al*,. 2012). The reduction in water levels for these dams would also mean that smaller farm dams would have been affected too. The farm’s ability to use additional irrigation to mitigate the effects of drought would then be significantly reduced. Therefore, it is important that the effects of drought on grapevine development are analysed both with and without the effect of irrigation.

1.6 Thesis Aims and Objectives

The aim of this study is to examine the impact of drought on the yields of wine grape cultivars in the Western Cape at farm and district scales. The specific objectives of the thesis are to:

(1) identify the temporal variation of drought at farm and district scales;
(2) classify the cultivar yields into groups based on their temporal variability;
(3) quantify the relationship between drought and grape yield at farm and district scales;
(4) evaluate how well a crop model simulates wine grape yields at farm scale; and
(5) identify the role of irrigation in mitigating the impact of drought on grape yields at farm scale.

The thesis is divided into seven chapters. A thorough review of the available literature related to the study is the focus of Chapter 2. Chapter 3 describes the data and methodology used in the study, while Chapter 4 presents the results and discussion at farm scale, and Chapter 5 presents the results and discussion at district scale. Chapter 6 presents and discusses the results of the crop modelling. Chapter 7 provides a summary of the key findings, reflects on the aims and objectives and the extent to which they have been met, and presents the concluding remarks of the study where future avenues for research/next steps are outlined.

Chapter 2: Literature Review

2.1 Climate and Grapevines

2.1.1 Grape Phenology

Studies have shown that the impact of climate on grapevines is crucial at three main phenological stages: bud-break, bloom, and ripening up to harvest, as well as during its dormancy (Ramos and Martinez-Casasnovas, 2010a; Jones and Davis, 2000). Bud-break, which is the first stage of growth, initiates during spring (September – October), when the average temperature exceeds 10 °C (Bruwer, 2010; Malheiro *et al*., 2010). The temperature during this stage plays a significant role in the timing of the forthcoming growth and development stages, which in turn will affect the yield. The timing of budding is strongly dependent on the duration of the vine's dormancy and its ability to achieve the required chill units (Lavee and May, 1997). In cases where adequate chill is not achieved, dormancy may be extended, thus budding will be shifted later in the season. The later occurrence of budding can cause erratic shoot and bunch numbers, which may reduce the yield, as experienced in some wine-growing areas in Australia (Web *et al*., 2007).

Temperature is not the only climate variable to play a part in the grapevine's growth and development; rainfall, which alters the soil moisture and provides water for the dams, is also significant. During this growth stage the amount of water available for optimal development is crucial; irrigation and no water restrictions are required for optimal growth (Malheiro *et al*., 2010; Ramos and Martinez-Casasnovas, 2010b). According to Ramos and Martinez-Casasnovas (2010b), the approximate amount of rainfall for a reasonable yield is 380 mm per annum. This would translate to an equivalent of irrigation in low rainfall areas. In certain areas of the Western Cape, 380 mm may constitute a good rain year; however it is not so much the amount of rain that falls in a season as the frequency with which it falls.

Since budding is the initial stage of growth, any impacts here will influence the growth and development during the subsequent stages. Therefore, if there is too much rain only early in the season, then there is a chance that the soils will become saturated and result in increased run-off. If there is no adequate supply of irrigation, the vines stand a chance of sub-optimal growth, as an early-season water deficit may occur. Although an early-season water deficit (which occurs during the Western Cape's rainfall period) is unlikely, reduced soil moisture during this period is not beneficial to the yield (Prichardt, 2003).

Following bud-break is the period of bloom, which initiates in late spring and early summer (November – December) (Myburgh, 2005). Studies show that optimal conditions during this stage are similar to that of bud-break, as warmer temperatures, as well as high soil moisture and ample irrigation or precipitation all promote growth in the plant (Malheiro *et al.*, 2010). Following bloom is the final growth stage, veraison, which initiates during summer (January – March) (Conradie *et al.*, 2002). Optimal conditions during this stage are a stable climate, specifically for diurnal temperature range and precipitation (Sadras and Soar, 2009). During this stage, the most significant climatic variable is considered to be precipitation, as deficit irrigation is required to provide optimum quality (Ramos and Martinez-Casasnovas, 2010b; Bruwer, 2010). Warm day-time temperatures and cool night-time temperatures are also required to ensure optimal quality during this stage (Jones *et al.*, 2005). During veraison, the effect of the soil water deficit (resulting from either climate or irrigation) can have a positive or negative impact on the fruit and the yield. High water deficits during this stage can result in sunburn and raisining of the grapes, which reduce the water content of the berries and thus reduce the yield (Prichardt, 2003). Similarly, excessive irrigation or rainfall can cause enhanced shoot growth which may cause additional shading, potentially leading to bunch rot and a reduced yield (Prichardt, 2003).

At the end of the veraison stage, all the farmers will harvest their grapes. This process is time- consuming and often overlaps with times during veraison. Since each cultivar grows differently, the exact timing of each stage may be slightly different and thus the above dates are considered approximations, as, in reality, when considering a group of cultivars, the stages all overlap.

2.1.2 Assessing Drought

A major obstacle in studying the relationship between drought and grape yields relates to using the most appropriate drought index to quantify drought intensity, as there is no unique and universal definition of drought. A drought index incorporates parameters from various meteorological and hydrological conditions such as temperature, rainfall, evapo-transpiration, and water supply indicators. Depending on availability of data and size of the study area, a number of drought indices can be used. Some of the more prominent drought indices include

Crop Moisture Index (CMI), Palmer Drought Severity Index (PDSI), Standardised Precipitation Index (SPI) and Standardised Precipitation Evapo-transpiration Index (SPEI).

CMI was developed by Palmer (1968) as a tool to monitor short-term changes in soil moisture. CMI uses evapo-transpiration deficit and soil water recharge to assess drought at a weekly time scale. This is one of the major shortcomings of the index, as it is not able to accurately monitor drought over long periods (Hayes, 2000). As a result, short-term weather influences will cause the index to portray the wrong assessment of drought in the area. This is such that rainfall from a small storm may briefly provide much needed soil moisture for crops and, through CMI, indicate that there is little drought, while, in the long term, a persistent drought may exist (Keyantash and Dracup, 2002). The shortcomings of this index would make it of little use in South Africa, where drought events persist for months at a time.

PDSI is an extensively used drought index, especially in the United States. This index is primarily used as a meteorological drought indicator which evaluates long-term wet and dry periods (Narasimhan and Srinivasan, 2005). It uses a generic two-layer water balance/soil model and variability in moisture supply to assess drought in a region. This, along with the use of Thornthwaite's equation (Trajkovic and Kolakovic, 2009), is the major downfall of this index. The model assumes an average water holding capacity for the topsoil over an entire region, although this is almost never the case. In reality, the characteristics of soil vary significantly over much smaller spatial scales such as farm lands or even crop blocks (Narasimhan and Srinivasan, 2005). The use of Thornthwaite's equation in calculating potential evapo-transpiration has yielded poor results, as evaluated by Jensen *et al*. (1990). It was suggested by Palmer (1965) that the Thornthwaite's equation should be replaced by a more appropriate method such as the FAO Penman-Monteith equation. In a country with high climate and soil variability, the shortcomings of this index make it unlikely to produce adequate results for assessing the impact of drought on grapevine yields in South Africa.

The most frequently used drought index for quantifying droughts in South Africa is the Standardized Precipitation Index (SPI), a multi-scale drought index developed in Mckee *et al*. (1993). This method is primarily a meteorological drought index which is based on rainfall at 3-, 6-, 9- and 12-month periods. In order to calculate SPI, rainfall during the aforementioned range is initially fitted to a gamma distribution, following which it is then transformed to a normal distribution (Keyantash and Dracup, 2002). This produces the dimensionless SPI values for a given range. Unlike CMI and PDSI, SPI accounts for the stochastic nature of rainfall and is thus a relatively good method for assessing both long- and short-term drought. There is however a major shortcoming of SPI in that it uses only rainfall for monitoring droughts, which assumes that rainfall has a stronger influence on droughts than any other climate variables (Sivakumar *et al.*, 2011; Vicente-Serrano *et al.*, 2011). Meanwhile, if a region receives the same amount of rainfall during two different seasons under different temperatures, the regions may be drier during the warmer season owing to higher evaporation.

Recently, Vicente-Serrano *et al*. (2010) proposed a new drought index: SPEI, which depends on the potential evapo-transpiration (PET). SPEI is a modification of the SPI and accounts for the effect of temperature variability in drought monitoring, and it can be computed at different time-scales. The process of calculating SPEI is based on a monthly or weekly balance between precipitation and PET which is adjusted using a 3-parameter log-logistic distribution to take into account common negative values (Potop, 2011). The popularity of SPEI is based on the incorporation of advantages of both PDSI and SPI. As such, SPEI makes use of the sensitivity of PDSI to changes in evaporation demand with the simplicity of calculation and multi-temporal nature of SPI (Potop, 2011). One of the key strengths of SPEI is its incorporation of PET in assessing drought. It is widely recognised that evapo-transpiration plays a significant role in determining soil moisture variability (Vicente-Serrano *et al.*, 2010). This means that the effect of evapo-transpiration on available soil moisture for crops is captured by SPEI in the calculation process. Similarly the multi-scalar nature of SPEI adds to the effectiveness of this index as agricultural drought (which generally consists of short-term drought indices) is accounted for. As a result, SPEI can be used to detect the temporal and geographical extension of droughts. This makes it a viable tool for drought monitoring and for assessing the future impact of global warming on droughts. This study employed SPEI as a drought indicator to determine the occurrence and extent of drought in the Western Cape.

2.1.3 The Effect of Drought on Yield

Viticulture is highly dependent on agro-meteorological conditions (Santos *et al.*, 2004) and these conditions are considered as the main driving force for good yields and high-quality grapes (Lisek, 2008). Since drought consists of temperature, rainfall and evaporative changes, it is important to consider each variable individually in order to accurately analyse its impact.

The most important of the meteorological conditions include temperature, solar radiation, humidity, precipitation and extreme events (Jones *et al*., 2005). The exact impact of each variable does not generally conform to any consensus amongst the relevant studies and their study areas. As a result, the impact of individual variables may differ depending on location and thus may not completely agree with the recent literature.

One of the arguments posed by many studies (*i.e.* Ramos and Martinez-Casasnovas, 2010a; Orduna, 2010) indicates that increases in temperature will have a negative effect on grape yields; however this is not always the case. As evident in studies by Jones *et al.* (2005) and Lisek (2008), increases in temperature have resulted in positive effects on the grapevines. This is accounted for in areas such as California and Poland, where the studies were performed. More specifically, Jones *et al.* (2005) and Cahill *et al.* (2007) identified that one of the positive effects promoting yields was a decrease in frost occurrence as a result of the increase in temperature. The associated increase in yield with increasing temperature is not the case for all grape-growing areas. An experiment conducted by Sadras and Soar (2009), in which they tested the effect of a 2 °C – 4 °C increase in mean temperature, indicated that yields from two out of the three vineyards had no significant change. Only one of the vineyards had a slight reduction in yield. What they identified was that the reduction in grape size was compensated by an increase in the number of grapes per bunch (Sadras and Soar, 2009). As for the negative impact of temperature, in Mediterranean climates, a decrease in the yield corresponds with the occurrence of long, dry periods with high temperatures (Ramos and Martinez-Casasnovas, 2010a). Increases in the average temperature above 25 °C or 30 °C severely decrease the photosynthetic capacity of the grapevine, which may result in a decrease in yield (Orduna, 2010). Other views for the temperature thresholds are presented by Malheiro *et al.* (2010), where the maximum threshold is 40 °C – 45 °C and minimum is 10 °C.

In a South African context, the scenario is slightly different, as Conradie *et al.* (2002) state that areas in the Western Cape that experience warmer temperatures often have lower yields than areas that have cooler temperatures. According to Bruwer (2010), the optimum temperature range for 90 % – 100 % photosynthesis is 18 °C – 33 °C. This is contrasted by Hunter and Bonnardot (2011) who state that the climatic requirements for optimal photosynthetic and physiological processes include temperatures between 25 °C – 35 °C, a diurnal temperature range of 25 °C – 30 °C (min/max) and relative humidity of 60 % – 70 %.

This suggests that the effect of temperature on grapes is not consistent between all the wine growing countries as well as the wine growing regions of South Africa.

Another variable that is considered to play a significant role in influencing wine-grape yields is quantity and distribution of precipitation (Malheiro *et al*., 2010). During years where there has been successive low rainfall or drought, high water deficits are likely to occur, and this has a significantly negative effect on the yield and quality of the grape (Prichard and Verdegaal, 2001). Ramos and Martinez-Casasnovas. (2010a) also stated that they found the lowest yields corresponded to the driest years. In addition to low rainfall, extreme precipitation events similarly have a significantly negative effect on yield (Jones *et al*., 2005). Extreme precipitation events lead to increased run-off, especially if there has been successive drought or levelling of the soil, which in turn causes water deficits and low yield (Jones *et al*., 2005). High precipitation, either throughout the growing season or between veraison and harvest, can cause many diseases, including bunch rot, which decrease the yield (Cahill *et al*., 2007; Prichard and Verdegaal, 2001).

The most significant variable that influences the canopy microclimate is solar radiation (Smart *et al*., 1990). Like temperature, solar radiation can have both positive and negative effects on grape yield. Smart *et al.* (1990) found that a canopy that is more exposed to solar radiation, increased photosynthesis in the plant and thus increased the yield. This idea is supported by Bruwer (2010), who concluded that a wide range of sunshine hours had a positive effect on yield. Solar radiation does not always have such positive effects on the yield. Increased exposure to solar radiation causes sunburn “raisining” of the grapes, which significantly decreases the weight of affected grapes and decreases the yield (Lisek, 2008).

2.1.4 Climate Change in the Western Cape

Climate change observed over the past 40 years shows that there has been an increased frequency of strong, late summer, low pressure systems, and a decrease in winter (Wooldridge, 2007). There has also been an increase in strong, late winter and early summer high pressure systems, which have enhanced the risk of fires (Wooldridge, 2007). The mean annual maximum and minimum temperatures have also increased over this period (Wooldridge, 2007). The rainfall trend for the mountainous areas in the Western Cape have either remained the same or increased slightly, whilst the trend for the low-lying areas is for a decrease (Wooldridge, 2007).

The projections for temperature change in the Western Cape show a general increase in mean minimum and maximum temperatures throughout the province, with an increase of approximately 1.5 °C in the coastal areas and approximately 2 °C – 3 °C in the inland areas (Midgley *et al.*, 2005). The projected increase in temperature will potentially increase the occurrence of extreme weather events, possibly from a higher frequency of cut-off low pressure systems with steep gradients that are associated with heavy rainfall and flooding (Wooldridge, 2007). Changes in the precipitation trends are also expected in the future for the Western Cape. Precipitation projections reported by Midgley *et al.* (2005) indicate a weakening in winter rainfall, possibly associated with a shift to more irregular rainfall that is more intense, and an increase in late summer rainfall in the interior and to the east of the Western Cape. The weakening in winter rainfall can be associated with a drying trend from west to east throughout the province (Midgley *et al.*, 2005). The decrease in winter rainfall can be associated with a shortening of the period in which cold fronts bring moisture to the continent (Wooldridge, 2007). Areas where the strongest change in late summer precipitation is expected is at mountains, where local orographic forcing creates the conditions for rainfall. This is associated with increased moisture in the atmosphere in the future (Midgley *et al.*, 2005). This suggests that there will be an increase in frequency and severity of drought events in the future, as associated with the predicted increase in temperature and decrease in rainfall. As such, the ability of farmers to mitigate the effect of drought through irrigation may be compromised, given the potential reduction in available water in dams and rivers.

2.1.5 Crop Management Adaptation

In order for farmers to adapt to the negative impact of drought events, they will have to optimise their management practices to ensure that they get an optimal output from each vine (Bindi and Howden, 2004). Of the management practices, irrigation and fertilisation are amongst the most significant in altering the yield and quality of the grapevines (Jackson and Lombard, 1993). Farmers' changing from spray irrigation to drip irrigation is just one of the management changes that can initiate a significant difference under a warmer climate. Since the Western Cape experiences high temperatures, spray irrigation is not adequate, as large amounts of the water evaporate before the vines are able to use them. Changing to drip irrigation conserves a significantly larger amount of water, as the water drops directly to where the vine roots are situated and thus the method optimises the available water for the grapevine (Caswell and Zilberman, 1984).

Apart from irrigation type, current and future drought may require a change in the current irrigation schedule for each farm. Simply applying irrigation as much as possible is not practical as dam levels may be lowered significantly, and it may have a negative effect on the yield. Irrigation towards harvest may be increasingly more difficult if dam water levels are low. Over-irrigating during the early growth stages could mean that there might not be enough water in the dams to continue with the regular irrigation schedule up to the harvest. Since harvest usually occurs from February (therefore encompassing the hottest months of the year), inadequate irrigation may result in significant yield loss (Prichardt, 2003). Alternatively, over-irrigating will cause vigorous vine and leaf growth which, in turn, will over-shade the grapes. This shading caused by excessive irrigating can cause yield loss and poor quality (Hunter, 1992). A study by Marshal and Utset (2000) shows that irrigation quantity, as well as irrigation timing, will be affected by climate change. From 2005 to 2025, there will be an increase in crop water demand during spring, as well as an 8 % increase in overall quantity (Marshal and Utset, 2000). This means that irrigation management will need to change to optimise it under these new conditions.

In a worst case scenario where optimal management practices are not adequate in countering the potentially negative effects of drought, the farmer will have to substitute either cultivars or crops. The warming trend proposed for the future may mean that specific cultivars, specifically the white varieties, will not cope, and, as a result, substituting the more temperature-resilient red varieties may ensure that the farming is still lucrative (Jones, 2007). If cultivar changes are not effective, then swapping to a more resilient crop may be beneficial. Changing from grapevines (high water dependency) to olives (lower water dependency) may be beneficial, as olives are tolerant of high temperatures, require less water than vines, and sell for a higher price (Bindi and Howden, 2004).

2.2 Crop Models

2.2.1 Model Types

Crop modelling is used extensively in the agricultural sector in order to perform a wide range of possible experiments, where statistical models and crop simulation models (CSM) are the most frequently used. The statistical models often use linear regression to simulate the relationship between agricultural productivity and the specific components within the equation (Singh, 2003). The model is based on a linear regression equation, $Y = A + b_1*X_1 + b_2*X_2 + \ldots + b_n*X_n$, where independent variables can be substituted into the equation to include their influence. These models, although simple when compared to more complex CSM, should not be disregarded, as they can often be accurate in analysing specific features of crop production. Research by Cahill *et al.* (2007) proved to be useful and relatively accurate when using statistical models to assess the climatic change impacts on wine grape yields in California. Statistical models are thus good at assessing the relationship between yield and individual variable sets, such as climate. These models are limited by their simplicity, as they do not take into consideration the interaction and feedback between different variables (Singh, 2003). This means that the results can often be misleading. Since these models can often only handle one specific set of variables at a time, the results will not include input from other important areas. This is the case for grapevines, where assessing yield includes a combination of climate, soil and management properties. As a result, more complex models (CSM) have been developed to analyse interactions between the crop and the external and internal influences.

CSMs are more complex than statistical models, as they incorporate biophysical processes in the crop in order to simulate crop growth with the influence of external variables such as soil, climate and management (Goldschmidt *et al.*, 2005). These models give a quantitative understanding of the effects of internal and external processes that result in crop growth (Singh, 2003). There are many applications for CSMs, as they combine features that originate from a broad spectrum of disciplines. Some of the main applications of CSMs include zoning (optimal areas to plant specific crops), yield predictions, climate change impacts, resource management and crop management optimisation (Singh, 2003). The focus of this study is on grapevine modelling, which is slightly different from other annual crops such as wheat and soybean, which have a lifespan of a few months (Goldschmidt *et al.*, 2005). A grapevine, which can be classified as a fruit tree, is planted approximately once every 35 years, contains a perennial "trunk" and has a very large number of reproductive and vegetative organs (Goldschmidt *et al.*, 2005). This makes it more complex to simulate grapevine growth than wheat and soybean. As a result of the complexity of the grapevine, there are a limited number of available models that contain a grapevine module and thus are capable of simulating grape growth. Some of the main (more complex) crop simulation models include DSSAT, STICS, VineLogic (phenology model), FENOVITIS (phenology model), APSIM, CropSyst, GRO and CERES. Of these models only APSIM (in prototype stage) and CropSyst have grapevine modules that are complex enough to accurately simulate grape growth in the Western Cape and allow for a range of simulations. The limited number of available grapevine crop models could account for the reason why there is a lack of CSM research available on the Western Cape.

2.2.2 Crop Model Research

CSMs have been used extensively over the past 40 years as a tool to simulate crop growth as well as other areas such as the impact of climate change on yield; however it appears that there is a lack of this research when focussing on wine grapes in the Western Cape. There have been a number of studies that focus on the impacts of climate change on yield, as well as other related areas such as phenology and grape quality, using either statistical or crop simulation models. There are currently numerous studies that have focussed on climate change and yields, such as those by Asseng *et al.* (2011), Mengistu (2011) and Žalud (2000), who used APSIM, GLAM or STICS models to assess the climate change impact on winter wheat. Other studies by McGlinchey (1999) and Chikowo (2008) used the CANEGRO and APSIM models to investigate the climate change impact on cane and maize production. It is thus fitting to emphasise that the majority of research identified that directly relates to yield projections are focussed on common crops such as wheat and maize. As a result, there is little identified research that uses crop simulation models to identify the impact of climate change on wine grape yields. This by no means shows that there have been no studies on wine grapes using crop simulation models, as many have been done. According to the majority of literature found on this topic, many people have chosen to use indices or thresholds when dealing with climate change and wine grape production. This is evident in studies by Hunter and Bonnardot (2011) and Jones (2007) that used Winkler and Huglin indices to approximate the future yields under climate change. A study by Carter (2006) used thresholds to associate change in the yield under climate change. There are also a number of studies that focus on climate change impacts on grapevine phenology, such as those from Caffarra and Eccel (2011), De Cortazar-Atauri (2009) and Web *et al.* (2007). These studies also use the changes in phenology as a proxy for yield changes in the future climate. There are also a number of studies that focus on the effect of climate change on wine grape quality, such as those from Web *et al.* (2008), Bruwer (2010) and Jones *et al.* (2005). Of the mentioned studies, only three were focussed on South African grapevines and, of these, none use crop simulation models to assess the impact of climate change on yield or have yield as their prime focus.

2.3 Summary

Drought events are common in the Western Cape, and it is important to identify the right drought index for any study. One of the newest drought indices is SPEI, which makes use of temperature, potential evapo-transpiration and rainfall at short and long time scales, and which may prove to be a useful tool in assessing drought in relation to crops such as grapevines. Although drought indices are able to identify drought in a region, the relationship between drought and yield is far more complex. Since drought is a combination of temperature- and rainfall-related variables, it is important to consider each impact separately. In terms of temperature, there is little consensus on the direct impact on grapevine yields. Alternatively, the effect of rainfall is more conclusive, as relatively higher rainfall almost always promotes greater yields. As a result, drought events will likely reduce yield, unless there is a greater relative change in temperature than rainfall. The effect of drought will also vary depending on the phenological stage present during the event. Similarly, the use of irrigation during drought events will likely mitigate some negative impact on yield.

From all the literature identified for this study, it would appear that there are almost no available scientific papers regarding the impact of drought on yield using SPEI or from a CSM perspective. This means that this study can contribute additional information on drought and grapevine yields that could help to improve the current knowledge base and mitigate negative impacts. It is clear from the literature that there is no general consensus on what is driving the climatic influence of drought on grapevine yields, as well as how the grapes will respond to future changes. A large aspect of this issue may be as a result of the zonal location of each wine growing area, as the climate, and thus influence of drought, is different relative to the location of the study area. The exact relationship between the drought and yield for the study area needs to be identified in order to attempt any understanding or insight into potential future conditions for the grape yields. Although there is an abundance of literature regarding the impact of climate on grapevine yield and quality, the surrounding climate/drought-yield literature for the Western Cape is limited. The use of CSMs for a qualitative or quantitative analysis of climate impacts on grapevine yields is an emerging field and needs to be explored and developed so that we can further our understanding in this field.

Chapter 3: Methodology

3.1 Study Area

South African grapes are predominantly planted in the Western Cape Province where the conditions are considered to be ideal. There are over 90 red and white grape varieties planted in the Western Cape that occupy a planted area of 101 016 ha (Whitehead and Uren, 2010). The vast number of cultivars planted in the province is located in several districts (Fig 3.1). Robertson, Olifants River and Stellenbosch districts have amongst the greatest distribution of vineyards. These three districts, collectively, contain over 40 % of the total planted area in the province and the grapes have been growing there since 2000 (Whitehead and Uren, 2010). Of the planted areas in the three districts, the Olifants River district contains the highest percentage of white grapes (70 % white and 30 % red), while Stellenbosch contains the highest percentage of red grapes (63 % red and 37 % white) (Whitehead and Uren, 2010). The most commonly planted red cultivar in the province is Cabernet Sauvignon, while Chenin Blanc is the most common white variety.

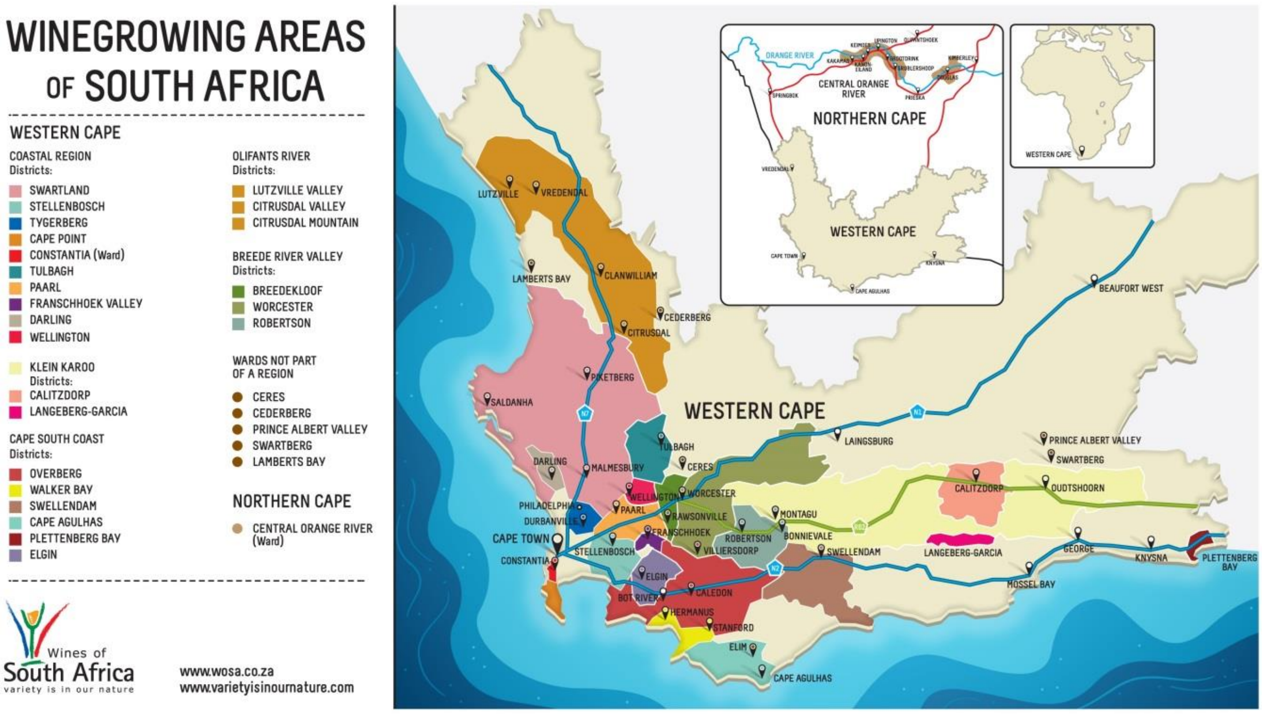

Figure 3.1. South African wine growing areas (http://www.wosa.co.za/sa/).

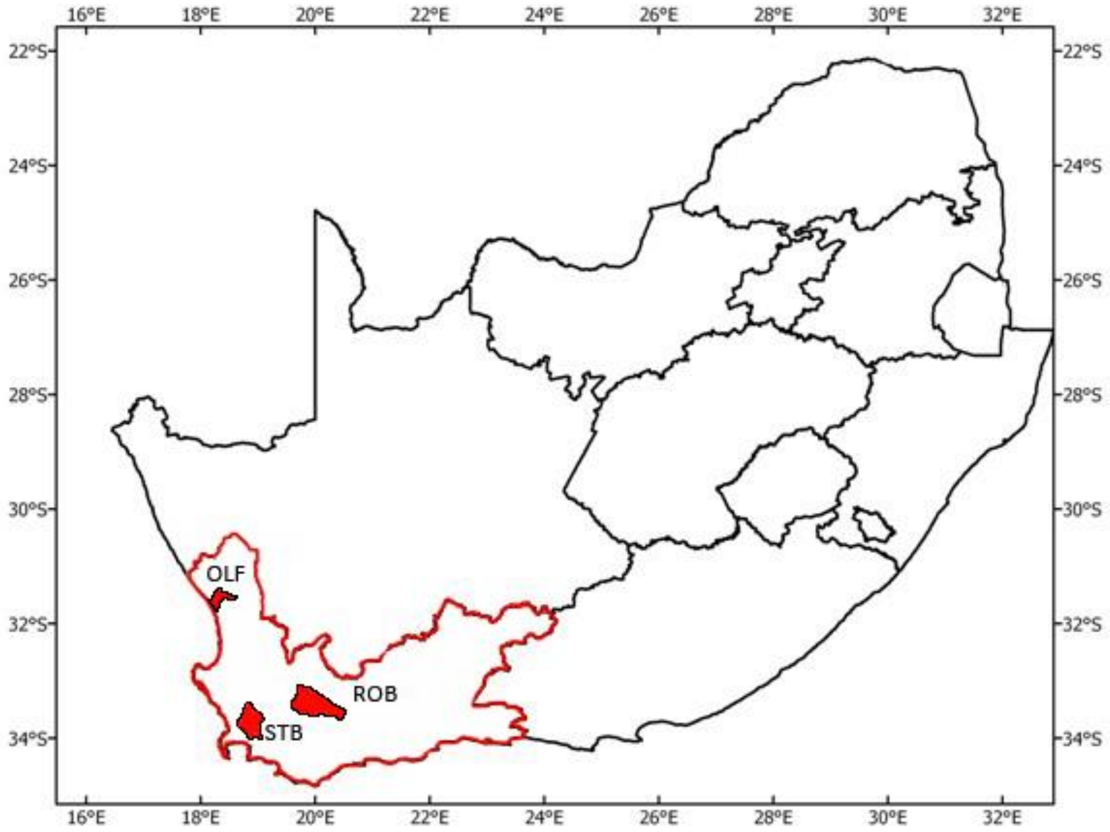

Figure 3.2. Map of South Africa showing the Western Cape (outlined in red) and Robertson (ROB), Olifants River (OLF) and Stellenbosch (STB) districts (filled in red).

The districts of Robertson, Olifants River and Stellenbosch all experience a Mediterranean-type climate, characterised by warm, dry summers and mild, wet winters; however, they vary significantly with regard to their location and climate (Lionello *et al*, 2006). In general these three districts are characterised by the similar wind types, Southerlies and South-Westerlies during the summer months and North-Westerlies during the winter months (Cape Winelands, 2007). The seasonal changes in wind direction are influenced by the dominating high or low pressure systems occurring at that time (Tyson and Preston-Whyte, 1988).

The Robertson district (33°48'S, 19°53'E, Fig 3.2) is located at 85 m – 250 m above sea-level (ASL), along the Cape Fold Belt Mountains. Temperatures throughout summer average from approximately 29 °C – 34 °C, with January and February being the warmest months (Cape Winelands, 2007; Conradie *et al*., 2002). The average temperatures during the winter period are approximately 4 °C – 8 °C (Cape Winelands, 2007). Precipitation patterns in the Western Cape vary and are dependent on microclimatic factors, such as the area's position relative to the ocean and topographical boundaries (e.g. the Cape Fold Belt ranges) (Tyson and Preston-Whyte, 1988). The Breede River Valley (where Robertson is located) receives approximately 467 mm of rain per annum, with areas like Worcester receiving only 200 mm during 2006 (Cape Winelands, 2007). Moisture and precipitation quantities vary significantly between the coastal and inland areas, mainly owing to the rain-shadow effect of the mountains (Bargmann, 2005). Features such as the Hottentot-Holland, Slanghoek and Du Toitskloof mountains play a significant role in blocking the passage of rain and moisture from the coast to the interior and thus may partly account for the higher temperatures and lower precipitation experienced in the Robertson/interior winelands (Bargmann, 2005; Midgley *et al*., 2005). The soils found in the Robertson area are either derived from low-lying sandy alluvial deposits or from the Cape Fold Belt shales, with some red clay and sand (WineSA, n.d.).

The Stellenbosch district (33° 55'S, 18° 51' E, Fig 3.2) is located at 136 m ASL and forms part of the coastal wine region (Bargmann, 2005). In comparison to the other two districts, this district receives the most precipitation, approximately 1600 mm – 1800 mm per annum, with a mean winter rainfall of 740 mm (Bargmann, 2005). Average temperatures for the coastal wine region are significantly affected by the cool Atlantic Ocean. Cool breezes from the ocean can affect mean February temperatures over 60 km inland (about 0.6 °C/km inland) (Bruwer, 2010). The Stellenbosch district experiences a warm, temperate climate, with summer temperatures (February) reaching a maximum of 28.1 °C and a mean annual temperature of 17.2 °C (Hunter and Bonnardot, 2011). The growing seasons in Stellenbosch are relatively warm, dry and humid which allow the grapes to perform very well. Similarly, the winter season is relatively cool, which allows the vines to achieve enough chill units to ensure good growth for the following season. The district is generally not located on flat ground, as it is surrounded by the Cape Fold Belt Mountains, which shelter some areas from colder weather (WineSA, n.d.). The main soils found in this district are red and yellow Tukulu and Oakleaf, which are dark alluvial to clay soils that give the many red wines a distinct flavour.

The Olifants River district (31° 39' S, 18°30E, Fig 3.2) is located at 34 m ASL. This district is located near the coast, similar to Stellenbosch, and receives a mean annual rainfall of 146 mm – 216 mm (Bruwer, 2010). This region is arid and relatively dry, which means that the successful cultivation of grapevines relies on the ability of a farm to apply adequate irrigation during the summer months. Similar to that of Stellenbosch, the influence of the sea-breeze plays a significant role in determining the temperature within the region. A 0.6 °C increase in temperature is experienced every 10 km inland (Bruwer, 2010). This results in a significant variability in temperature within the district. The Olifants River district has a very diverse topography, being relatively flat in the north (Olifants River basin) and mountainous to the south (Cederberg mountains). The region boasts the world's highest (altitude) wine growing area, in which Cederberg Private Cellar is situated above 1150 m ASL (WineSA, n.d.). The main soils found in the districts include alluvial riverbank soils, which are largely made up of clay and "Karoo" soils, which are typically sandy and may contain lime.

3.1.1. Climate of the study areas

The seasonal variation of rainfall and temperature in the 3 districts (Robertson, Stellenbosch and Olifants River; Fig 3.1) typifies that of a Mediterranean climate, which is characterised by warm dry summers and mild wet winters (Ziervogel *et al*., 2010). In the 3 districts, the highest rainfall occurs in June – August (JJA, winter) for Stellenbosch and the lowest in Olifants River, which also reports the lowest summer rainfall. Hence Stellenbosch has the highest annual rainfall (approximately 56mm) and Olifants River the lowest (approximately 18mm). Although the 3 districts receive rainfall from the same synoptic features (i.e. frontal systems, Tyson and Preston-Whyte, 1988), orographic forcing could make rainfall higher in Stellenbosch and Robertson (which are located in mountainous areas) compared to Olifants River (where it is typically flatter). Through the year, the highest minimum temperature (TMN) and maximum temperature (TMX) occur in Olifants River while values for Stellenbosch and Robertson are very close. The location of Olifants River, equatorward of Robertson and Stellenbosch, could be a major reason why TMN and TMX are higher in Robertson and Stellenbosch; another reason is that Olifants River is located at a lower elevation than the other 2 districts. The lowest TMN occurs in Robertson while values for Stellenbosch and Olifants River are very close. This is due to the moderating influence of the ocean, with Stellenbosch and Olifants River being situated closer to the ocean than Robertson.

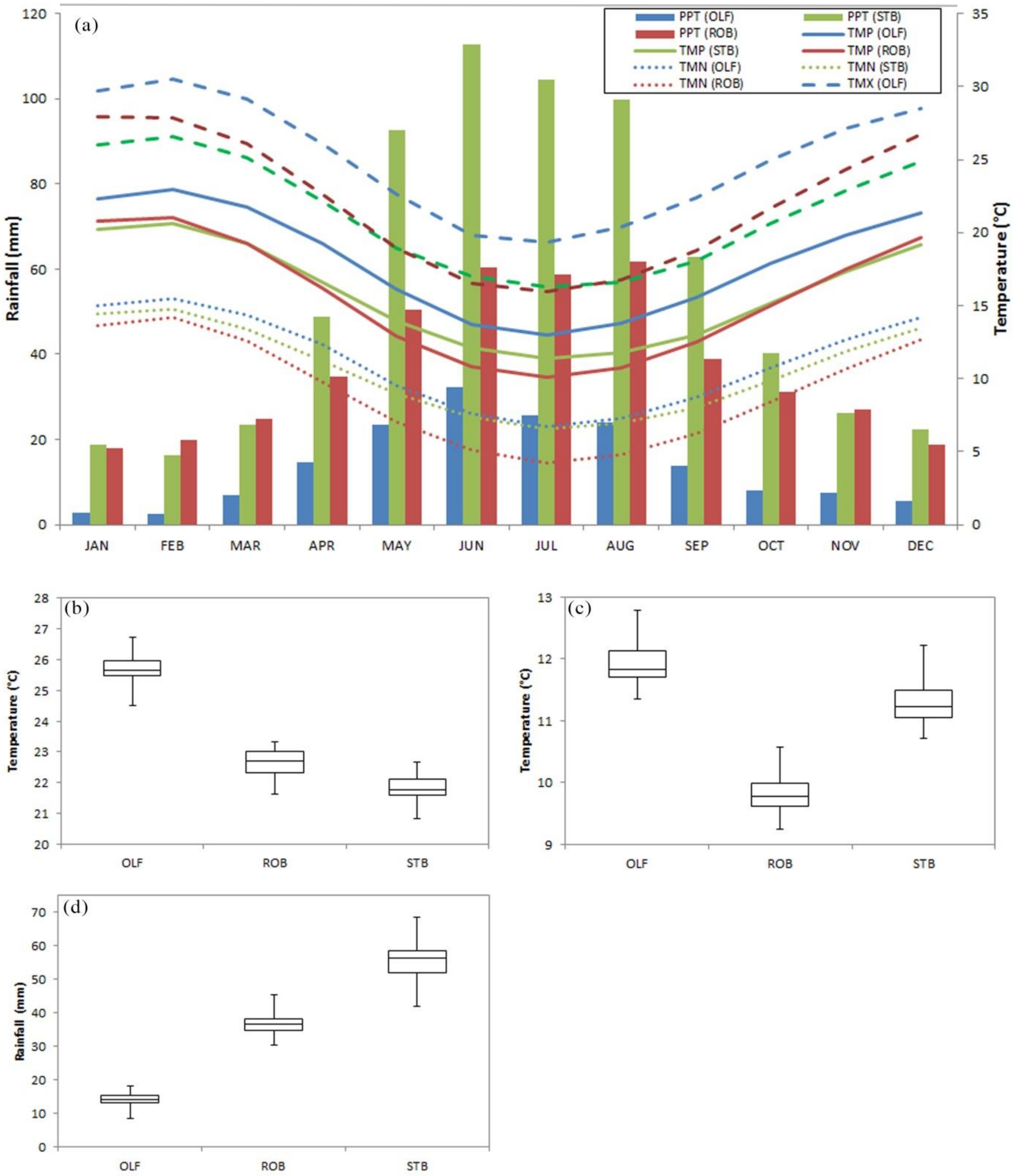

Figure 3.3. Climatology of Robertson (ROB), Olifants River (OLF) and Stellenbosch (STB). Panels: (a) mean monthly climatology, (b) maximum temperature variability, (c) minimum temperature variability, (d) rainfall variability (CRU; Mitchell *et al*., 2004).

The variability of temperature (mean temperature (TMP), TMX and TMN) and precipitation varies both on monthly and annual scales, as well as between each district (Table 3.1). On the annual scale, the highest rainfall variability (15.7 mm) is in Olifants River and the lowest (11.7 mm) in Stellenbosch; the highest mean temperature variability (2.4 °C) is in

Stellenbosch and lowest in Olifants River; and the highest maximum temperature variability (2.1 °C) and minimum temperature variability (3.3 °C) is in Robertson and the lowest in Olifants River (1.7 °C and 2.9 °C respectively). The variability of all the climate variables at a monthly scale is higher for all three districts than at an annual scale. The highest monthly precipitation variability is 47.8 mm, whereas its highest annual variability is only 15.7 mm. The highest monthly mean temperature variability is 6.74 °C, compared to its annual variability of 2.4 °C. The highest monthly maximum temperature variability is 6.7 °C, whereas its annual variability is 2.1 °C. Lastly, the highest monthly minimum temperature variability is 14.3 °C, compared to its annual variability of only 2.9 °C. Not only does the highest variability occur on a monthly scale, it tends to be highest during the winter months (JJA) for all four variables, which suggests that the climate variability is associated with the mid-latitude storm track. This is such that increased frontal activity will increase the variability of rainfall and temperature variables.

3.2 Data

The study analysed climate data and grape yield data from two stations (Langverwacht and Vink Rivier) and three districts (Robertson, Olifants River and Stellenbosch). The Langverwacht station (33.9366S, 20.01519E) provides climate information for Prospect and Boesmansdrift farms located in the vicinity of the station (less than 8km away), hence both farms are considered part of Langverwacht in this study. The grape cultivars grown on the farms are Ruby Cabernet, Sauvignon Blanc, Merlot and Chardonnay. This study used the yield data from all the cultivars, except that the data covers different time periods (Table 3.2). The Vink Rivier station (33.70236S, 19.71503E) also shares climate information with Orange Grove farm located 2km away; hence the farm is considered Vink Rivier farm in this study. Vink Rivier farm grows Shiraz and Colombar cultivars; the yield data from both cultivars are analysed in this study (Table 3.2). All of the farms used in this study are located in the Robertson district and are considered to be small-medium sized, as they have at least 20ha of vineyards. The data acquired for each farm were supplied from the farm managers by a recorded history or their knowledge. Soil specific data was supplied by IT Measure, which manages probes located at varying depths in each cultivar block. The soils, which differ for each cultivar and each farm, include shale, clay/sand, sandy loam and red clay. Although each farm fertilises and irrigates different quantities at different times, they all use a similar drip-style irrigation method.

The Robertson district (33°48'S, 19°53'E) is located at 85 – 250m above sea level (ASL), along the Cape Fold Mountains, while the Olifants River district (31°39'S, 18°30E) is located at 34m ASL, and the Stellenbosch district (33°55'S, 18°51'E) at 136m ASL. The districts experience a Mediterranean climate, characterised by warm, dry summers and mild, wet winters (Lionello *et al.*, 2006). For the study, we obtained the climate data (rainfall and temperature; 1984 – 2009) for the three districts from the Climatic Research Unit (CRU; Mitchell *et al*., 2004). CRU is a gridded dataset which provides a more general representation of climate over a large area than that of a single station, which may be biased by its location and topography. The farms in each district cultivate a large variety of grapevines; but Cabernet Sauvignon (red variety) and Chenin Blanc (white variety) are the largest cultivars grown in the districts (WineSA, n.d.). For the present study, grape yield data for 26 years (1984 – 2009) were analysed over each district. The grape yield data, obtained from the South African Wine Industry Information and Systems (SAWIS), consist of grape yield (expressed in kg ha^{-1}) of 35 grape cultivars (Table 3.3) from all the registered wine farms in the three districts. The farms differ in soil type, grape variety, and management practices; hence it is difficult to assume the same management protocol for all the farms. However, the common management practices in the districts include: pruning once a season (from the beginning of August); fertilization twice in a season (after harvest and the beginning of August); regular irrigation (about six hours per day) during early growth, depending on rainfall for the season and the amount of available water in the dams; and less irrigation during ripening and harvest, depending on temperature and soil moisture.

Table 3.1. Coefficient of variability for monthly and annual climates of Robertson, Olifants River and Stellenbosch (CRU; Mitchell *et al*., 2004).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
Precipitation (mm)													
Olifants River	28.6	37.4	40.6	51.8	49.5	57.3	41.3	39.9	34.3	54.6	30.8	42.4	15.7
Robertson	45.7	29.1	44.3	55.1	47.1	38.3	39.4	44.6	44.1	58.5	55.5	42.1	10.6
Stellenbosch	35.8	35.5	44.5	54.8	46.9	41.5	39.7	40.9	47.4	57.6	47.8	38.7	11.7
Mean Temperature (°C)													
Olifants River	4.0	3.7	4.1	4.5	5.4	5.9	6.7	5.9	6.5	5.7	4.9	3.9	1.9
Robertson	3.5	3.1	3.7	4.3	4.8	6.3	6.6	6.4	6.0	5.0	5.3	4.0	2.2
Stellenbosch	3.6	3.4	3.9	4.3	4.4	5.7	6.2	5.8	5.9	5.3	5.4	4.4	2.4
Maximum Temperature (°C)													
Olifants River	3.1	3.3	3.6	4.3	5.1	5.5	5.9	5.7	6.5	5.4	4.6	3.6	1.7
Robertson	2.6	2.7	3.2	4.5	4.9	6.7	6.3	5.5	5.4	4.8	4.6	3.3	2.1
Stellenbosch	2.9	2.9	3.6	4.1	4.5	5.8	6.3	5.0	5.5	4.9	4.9	3.8	2.1
Minimum Temperature (°C)													
Olifants River	6.4	5.6	5.9	7.0	9.5	11.3	12.4	9.1	8.1	8.8	6.4	5.6	2.9
Robertson	6.0	5.3	6.0	6.8	9.7	12.0	14.3	13.7	9.5	8.6	8.8	7.0	3.3
Stellenbosch	5.2	5.1	5.4	5.7	6.8	9.4	10.0	10.0	7.7	7.4	7.2	5.9	3.2

Table 3.2. General characteristics of observed yield data (Goussard, 2008).

Cultivar	**Type**	**Year**	**Farm**	**Yield (ton/ha)**	**Berry Size**	**Budding**	**Ripening**	**Climate**
Ruby Cabernet	Red	1999 - 2013	Boesmansdrift	5-9	Small	End Aug-Begin Sept	End Feb	Prefers cool climates, sensitive to frost
Sauvignon blanc	White	2004 - 2013	Boesmansdrift	15-20	Medium	End Aug-Begin Sept	Begin Mar	Prefers warm-temperate climates, sensitive to frost
Merlot	Red	2005 - 2013	Prospect	9-13	Medium-Small	Begin Sept	Mid Feb	Prefers cool climates, sensitive to frost
Chardonnay	White	2008 - 2013	Prospect	8-12	Medium	Begin Sept	Begin Mar	Prefers cool climates
Shiraz	Red	2008 - 2013	Orange Grove	20-30	Small	Begin Sept	End Mar	Prefers warm climates
Colombar	White	2008 - 2013	Orange Grove	10-15	Medium	Mid Sept	End Feb-Begin Mar	Prefers warm climates

Table 3.3. General characteristics of cultivars at district scale (Goussard, 2008).

Cultivar	Yield (tons/ha)	Berry Size	Budding	Ripening	Climate
White					
Bukettraube	16-20	Medium	Begin Sept	End Feb	Prefers cool climates, sensitive to wind
Chardonnay	5-9	Small	End Aug-Begin Sept	End Feb	Prefers cool climates, sensitive to frost
Chennel	16-20	Medium	Begin Sept	End Feb-Begin Mar	Prefers cool climates, sensitive to frost
Chenin Blanc	20-23	Small	End Aug-Begin Sept	End Feb	Performs well in a wide range of climates
Clairette Blanch	16-18	Medium-Small	End Sept	End Mar	Prefers cool climates, sensitive to wind
Colombar	15-20	Medium	End Aug-Begin Sept	Begin Mar	Prefers warm-temperate climates, sensitive to frost
Fernão Pires	15-20	Medium	End Aug-Begin Sept	Begin Feb	Prefers cool-warm climates
Gewürztraminer	10-12	Small	End Aug	Begin Feb	Prefers cool climates
Hárslevelü	18-20	Medium	Begin Sept	End Feb	Performs well in a wide range of climates
Mario Muscat	16-18	Medium	End Aug-Begin Sept	Begin Feb	Prefers cool-warm climates
Raisin Blanc	>20	Large	End Sept	End Mar-Begin Apr	Prefers mild-temperate climates
Sauvignon Blanc	9-13	Medium-Small	Begin Sept	Mid Feb	Prefers cool climates, sensitive to frost
Sémillon	10-15	Medium	Begin Sept	Mid Feb	Prefers cool climates, very sensitive to wind
Ugni Blanc	>20	Medium	Mid Sept	Begin-Mid Mar	Prefers cool climates
Weisser Riesling	10-12	Medium-Small	Begin Sept	End Feb-Begin Mar	Prefers cool climates
Weldra	22-27	Medium	End Sept	End Feb-Begin Mar	Prefers cool climates
Red					
Carignan	15-20	Medium	Mid Sept	End Mar	Prefers warm climates
Cabernet Sauvignon	15-20	Small	End Sept	End Mar	Prefers semi-arid climate and high temperatures
Gamay Noir	12-15	Medium	Begin Sept	Begin Feb	Performs well in a wide range of climates
Merlot	8-12	Medium	Begin Sept	Begin Mar	Prefers cool climates
Muskadel (red)	15-20	Small-Medium	Begin Sept	End Feb	Prefers warm climate
Pinotage	10-15	Small	Begin Sept	End Feb	Prefers high temperatures
Pinot Noir	8-14	Small	Begin Sept	Begin Feb	Tolerant to cold temperatures, sensitive to frost
Ruby Cabernet	20-30	Small	Begin Sept	End Mar	Prefers warm climates
Shiraz	10-15	Medium	Mid Sept	End Feb-Begin Mar	Prefers warm climates
Tinta Barocca	16-20	Medium	Begin Sept	Mid Mar	Prefers warm climates

3.3 Calculation of drought index (SPEI)

The study used SPEI, developed by Vicente-Serrano *et al*. (2010), to characterize droughts at the station and district scales. SPEI uses a water balance (D, which is the difference between precipitation and potential evapo-transpiration) to describe drought at any location. SPEI is usually obtained by fitting a log-logistic (gamma or Pearson III) distribution to D. The value of SPEI typically ranges from -3 to 3 in depicting the intensity of dryness (drought; negative values) to wetness (positive values); the SPEI description of drought intensity is given in Table 3.4. This study adopted the SPEI library (Beguería and Vicente-Serrano, 2013) in the R software (R Development Core Team, 2012), which was used to compute the SPEI over each station and district at 3-month scales, using the monthly rainfall and temperature data. The temperature data was used to calculate the potential temperature using Thornthwaite's method (Vicente-Serrano *et al*., 2010). The computation of SPEI at 3-month scale is necessary, as scale coincides with the key stages of grapevines phenology.

Correlation analysis was used to quantify the relationship between the drought index and grape yields at station and district levels. For the station level, the seasonal SPEI (DJF, MAM, JJA and SON) at each station was correlated with yield data of each cultivar at the station. For district level, the seasonal SPEI at each district was correlated with yield group at the district. The seasonal SPEI at a district was also correlated with individual cultivars at the district. In the correlation, the SPEI for post-harvest seasons (JJA, SON) for a year were correlated with the grape yield of the following year. Similarly, seasonal temperature and rainfall were correlated with district yields (yield groups as well as individual yields), as well as the individual farm yields. The seasonal temperature and rainfall data were calculated using a 3-month rolling average, similar to that of the SPEI seasons.

Table 3.4. The 7 classes of SPEI category according to value (Potop *et al*., 2013).

SPEI	**Category**
≥2	Extreme Wet
1.5 to 1.99	Severe Wet
1.49 to 1.00	Moderate Wet
0.99 to -0.99	Normal
-1.00 to -1.49	Moderate Drought
-1.50 to -1.99	Severe Drought
≤-2.00	Extreme Drought

3.4 Grouping of grape yields at each district

The yields of the cultivars can be grouped based on their phenology, colour (reds and whites), farm soil type, farm management, or inter-annual variability. Since the emphasis of this study is on inter-annual variability of the yields, we grouped the yields based on their inter-annual variability, using the Principal Component Analysis (PCA). PCA is a statistical technique for data analysis and processing used for dimensionality reduction. In any work involving data analysis, it is common to come across data which has multiple variables. The information in many of the variables is often redundant; with very few sources of valuable information. It is therefore necessary to use dimensional reduction to extract the processes described in the data. PCA is capable of identifying processes that control the variability of variables in large datasets. It can identify the relationships between the variables and recognise which variables are significantly correlated (Shlens, 2005). It identifies unknown variability in the dataset and displays the information in a way that highlights both the similarities and differences (Smith, 2002). Here, the PCA was applied to classify the grape yields (cultivars) into groups (principal factors) that represent significant inter-annual variation in the yield dataset. Hence, the results of the PCA helps to reduce the dimension of the yield data from 14 (cultivars) to three (principal factors). The inter-annual variability (score) of each principal factor is studied with respect to individual grape (cultivar) yields that show high loadings for principal factors. This analysis was used on the district-scale yields in order to make the data more manageable. Thus yield groups (principal factors) were generated for Robertson, Olifants River and Stellenbosch.

3.5 Grape yield simulation: model description and experimental set-up

The study applied the Agricultural Production Systems Simulator (APSIM) crop model to simulate grape yields. It incorporates vital aspects of cropping dynamics including crop depth, response to climate or soils, erosion, fallows, long-term soil processes, and residues (Keating *et al*., 2003). The model simulates biological and physical processes, such as the growth, development and yield of crops. The current vine module is a prototype and is a sub-module of the PLANT 2 module. The grapevine crop module, VINE, describes the development, growth, yield, water uptake in response to climate, soil, management and stress factors in grapevines on a daily time step. The VINE module makes extensive use of the soil water module, which simulates the various vertical water movements in a layered soil system using a multi-layer cascading approach (Asseng *et al*., 1998). The water characteristics of the soil are specified in terms of the lower limit (LL15), drained upper limit (DUL) and saturated

(SAT) volumetric water contents of a sequence of soil layers. Phenology is determined by thermal time and is calculated from 3-hourly air temperatures interpolated from the daily maximum and minimum temperatures. The grapevine phenology is represented as progression from dormancy to budding, shoot growth, flower development, berry development, ripening and senescence. Management is used to call a set of rules or calculations supplied from sub-routines which are specific for each individual module; for instance, the irrigation module, which allows one to specify the irrigation type, amount and applicable conditions (Keating *et al.*, 2003).

APSIM requires information on meteorological conditions (daily minimum and maximum temperature, solar radiation and rainfall), soil characteristics (up to a depth of 80cm at 20cm intervals), and management practices for a farm as input data to simulate the cultivar growth and yield on the farm. For the present study we used the meteorological, soil and management data from Langverwacht and Vink Rivier in the APSIM simulation for each cultivar. Temperature, rainfall and solar radiation data were supplied by the ARC-ISWC. This data was then adjusted to the APSIM MET file format and used to calculate annual average ambient temperature (TAV) and annual amplitude in mean monthly temperature (AMP) for each station. The climate, soils and management data were used to initialise the model, after which the wine grape yields (MOD) were generated for each cultivar. Since APSIM does not currently have a yield function, Berry Live Fresh Weight (BerryLiveFWt) was used to approximate yield. Since yield is essentially the total mass of berries, using BerryLiveFWt would be acceptable (as suggested by the model developer). More information regarding the individual cultivar input data is available in Tables 3.5 – 3.8. In assessing the sensitivity of the drought-yield relationship to irrigation management, the simulations were initialised in the same way as mention previously, except for the management input. In these simulations, irrigation management was removed completely and the yields ($\mathrm{MOD_{rm}}$) generated.

The simulated yields are evaluated with reference to observed yield at each farm. The evaluation includes calculation of root mean square errors of the simulated yield and correlation between the simulated and observed yields. We also compared standard deviation of the simulated yield with observation, and examined how well the model couples the simulated yield with the drought index at each station. In assessing the model's ability to simulate sign changes in the yield, we used synchronisation (Misra, 1991). Synchronisation is defined as:

$$\eta = \left(\frac{\mathrm{n} - n^{/}}{\mathrm{n}}\right) \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $n^{/}$ is the number of years that the simulated yield is out of phase with the observed yield and n is the total number of years under study. Furthermore, we explored the impacts of irrigation and fertiliser management on the simulated yield and on the coupling between the simulated yield and drought index.

Table 3.5. Vine Extensible Markup Language (XML) thermal time XY pairs. XML is a markup language that defines a set of rules for encoding documents in a readable format. The XY pairs are sourced from the APSIM Vine Module code. Data sourced from the XML code.

Thermal Time XY Pairs		Dormancy Thermal Time XY Pairs	
7	0	0	0.0
26	15	1	1.0
34	15	6	1.0
39	0	19	0.0

Table 3.6. Vine Extensible Markup Language (XML) phenology XY pairs. The XY pairs are sourced from the APSIM Vine Module code. Data sourced from the XML code.

Stage	XY Pairing
Dormancy	45
Bud Burst	210
Shoot Growth	230
Flower Development	210
Berry Development	460
Ripening	730

Table 3.7. Irrigation Characteristics for 6 cultivars from Prospect, Orange Grove and Boesmansdrift farms (sourced from IT Measure): Available Soil Water Depth (ASW Depth), Fraction of ASW below which irrigation is applied (ASW Fraction), Irrigation Efficiency and irrigating based on rainfall being less than "x" over the last few days (BOR).

	Ruby Cabernet	Sauvignon Blanc	Merlot	Chardonnay	Shiraz	Colombar
ASW Depth (mm)	800	800	800	800	800	800
ASW Fraction (0-1)	0.66	0.75	0.69	0.58	0.75	0.69
Efficiency	0.9	0.9	0.9	0.9	0.9	0.9
BOR (mm)	20	5	5	5	20	20

Table 3.8. Planting Characteristics for 6 cultivars from Prospect, Orange Grove and Boesmansdrift farms (sourced from the respective farm managers).

	Ruby Cabernet	Sauvignon Blanc	Merlot	Chardonnay	Shiraz	Colombar
Sow Date	12-May	10-May	10-May	12-May	12-May	10-May
Sow Density (Plants/m2)	3.73	3.75	4.05	3.75	3.00	3.00
Row Spacing (mm)	2400	2500	2700	2700	2500	2500
Prune	20-May	20-May	20-May	20-Jun	20-May	20-May
Bud Number	92	92	92	92	92	92
Max Crop Cover	0.5	0.5	0.5	0.5	0.5	0.5

Table 3.9. Fertiliser characteristics for 6 cultivars from Prospect, Orange Grove and Boesmansdrift farms (sourced from the respective farm managers).

Cultivar	Fertiliser	Amount (kg/ha)	Type
Ruby Cabernet	01-Mar	150	Urea N
	03-Aug	150	Urea N
Sauvignon Blanc	01-Mar	300	Urea N
	28-Jun	300	Urea N
Merlot	01-Mar	789	Urea N
	28-Jun	789	Urea N
Chardonnay	01-Mar	789	Urea N
	03-Aug	789	Urea N
Shiraz	01-Mar	60	Urea N
	28-Jun	60	Urea N
Colombar	01-Mar	100	Urea N
	28-Jun	100	Urea N

Table 3.10. Soil characteristics for 6 cultivars from Prospect, Orange Grove and Boesmansdrift farms (sourced from IT Measure) for: Aridry, 15 Bar Lower Limit (LL 15), Drainage Upper Limit (DUL), Saturated Water Content (SAT), Vine Lower Limit (Vine LL), Vine Plant Available Water Content (Vine PAWC), Vine available soil Water Factor (Vine KL), Root Exploration Factor (Vine XF) and Saturated Water Conductivity (SWCON).

Cultivar	Depth (cm)	Airdry (mm/mm)	LL 15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	Vine LL (mm/mm)	Vine PAWC (mm/mm)	Vine KL (/day)	Vine XF (0-1)	SWCON (0-1)
Ruby Cabernet	0-20	0.03	0.101	0.145	0.145	0.101	8.8	0.1	1	0.015
	20-40	0.04	0.104	0.149	0.149	0.104	9	0.1	1	0.008
	40-60	0.025	0.096	0.138	0.138	0.096	8.4	0.06	1	0.008
	60-80	0.03	0.101	0.145	0.145	0.101	8.8	0.03	1	0.008
Sauvignon Blanc	0-20	0.04	0.113	0.151	0.151	0.113	7.6	0.1	1	0.012
	20-40	0.03	0.111	0.148	0.148	0.111	7.4	0.1	1	0.01
	40-60	0.025	0.109	0.146	0.146	0.109	7.4	0.06	1	0.008
	60-80	0.03	0.111	0.145	0.145	0.111	6.8	0.03	1	0.008
Merlot	0-20	0.05	0.1	0.165	0.165	0.1	13	0.1	1	0
	20-40	0.115	0.14	0.17	0.17	0.14	6	0.1	1	0
	40-60	0.108	0.108	0.18	0.18	0.108	14.4	0.06	1	0
	60-80	0.111	0.111	0.185	0.185	0.111	14.8	0.03	1	0
Chardonnay	0-20	0.03	0.105	0.145	0.145	0.105	8	0.1	1	0.011
	20-40	0.04	0.13	0.158	0.158	0.13	5.6	0.1	1	0.002
	40-60	0.04	0.12	0.149	0.149	0.12	5.8	0.06	1	0.007
	60-80	0.04	0.13	0.154	0.154	0.13	4.8	0.03	1	0.007
Shiraz	0-20	0.03	0.101	0.145	0.145	0.101	8.8	0.1	1	0.015
	20-40	0.04	0.104	0.149	0.149	0.104	9	0.1	1	0.008
	40-60	0.025	0.096	0.138	0.138	0.096	8.4	0.06	1	0.008
	60-80	0.03	0.101	0.145	0.145	0.101	8.8	0.03	1	0.008
Colombar	0-20	0.04	0.142	0.184	0.184	0.142	8.4	0.1	1	0.011
	20-40	0.05	0.138	0.178	0.178	0.138	8	0.1	1	0.09
	40-60	0.05	0.127	0.163	0.163	0.127	7.2	0.06	1	0.014
	60-80	0.03	0.113	0.145	0.145	0.113	6.4	0.03	1	0.012

Chapter 4: Results and Discussion (1) - Drought and Grape Yield at Farm Scale

4.1 Temporal variability of drought index at farm scale

The temporal variation of SPEI at the two stations (Langverwacht and Vink Rivier; Figs. 4.1 and 4.2, respectively) shows that both stations have experienced moderate and severe droughts in the past few years (1999 – 2013 and 2008 – 2013, respectively). At Langverwacht (Fig. 4.1), there were two major (long) dry periods (around 1999 and 2010) and two minor (short) periods (in 2005 and 2013) with at least moderate droughts. The two major dry periods lasted for more than 18 months, featuring moderate droughts (SPEI ≤ -1.0) for almost one year and severe drought (SPEI ≤ -1.5) for more than 10 months. Each of two minor dry periods lasted for six months, each featuring moderate droughts for about three months. However, the station also experienced intermittent wet conditions with moderate wet (SPEI ≥ 1.0) to severe wet (SPEI ≥ 1.5) periods. The moderate wet conditions lasted for about five months in 2002, four months in 2006 and four months in 2008. On the other hand, at Vink Rivier station, there was one major and one minor dry period with at least moderate drought. The major drought event occurred in 2010 (in phase with that of Langverwacht), featuring a severe drought that lasted for about seven months, followed by the minor drought, which occurred from 2012 – 2013 and was a moderate drought lasting only two months (Fig. 4.2). The station also featured one severe wet period (2008 – 2009) and one moderate wet period (2012) (Fig. 4.2). Since the two stations are close to each other, it is no surprise that the severe drought of 2010 reflected in both stations.

Note that, in most cases, the drought conditions are associated with negative anomalies in rainfall and positive anomalies in temperature, while wet conditions are associated with positive anomalies in rainfall and negative anomalies in temperature. For instance, in both stations, the drought of 2010 was owing to deficit in rainfall amount (about 80 % at Langverwacht and 55 % at Vink Rivier) and warmer temperature (about 0.1 ^{o}C at Langverwacht and 0.4 ^{o}C at Vink Rivier). The same is true of the drought of 1999 at Langverwacht (rainfall decreased by 38 % and temperature increased by 1.6 ^{o}C). A negative rainfall anomaly with positive temperature seems to produce more severe drought than with negative temperature anomalies. For instance at Langverwacht (Fig. 4.1), though the rainfall deficit was higher in 2001 (about 50 %) than in 1999 (about 35 %), the drought was more severe in 1999 than in 2001 because the temperature was higher (owing to evaporation) in 1999 than in 2001. This is consistent with previous studies (Vicente-Serrano *et al.*, 2010) that argued that quantifying droughts only with SPI (*i.e.* rainfall only) may underestimate the severity of the droughts.

Interestingly, the severe drought condition of 2010 coincided with the El Niño event known to produce drought over South Africa (Dufois and Rouault, 2012). The severe wet conditions of 2006 and 2008 also occurred with the La Niña events, which induces wet conditions in South Africa (Dufois and Rouault, 2012). The minor dry conditions in both stations fall within the neutral phase of ENSO events. The results agree with previous studies (*i.e*. Meque and Abiodun, 2014) that associated El Niño with severe drought owing to rainfall deficit and higher temperature (hence, deficit water balance in the soil), and La Niña events with wet conditions owing to more rainfall and lower temperature (*i.e*. surplus water balance in the soil).

Hence, the results show the occurrence of drought over the two stations and show that the severity of the drought was sensitive to temperature anomalies over the station. This suggests that identifying drought over the two stations using SPEI (based on rainfall and temperature) may give a more realistic picture of drought intensity than using the SPI (based on rainfall only). Occurrence of severe drought or severe wet conditions over the stations depends on the ENSO events; however, moderate droughts may occur during the neutral phase on the ENSO event. Thus, a further increase in temperature with a decrease in rainfall, or the strengthening of ENSO events, in the future may enhance drought occurrence and intensity over the stations.

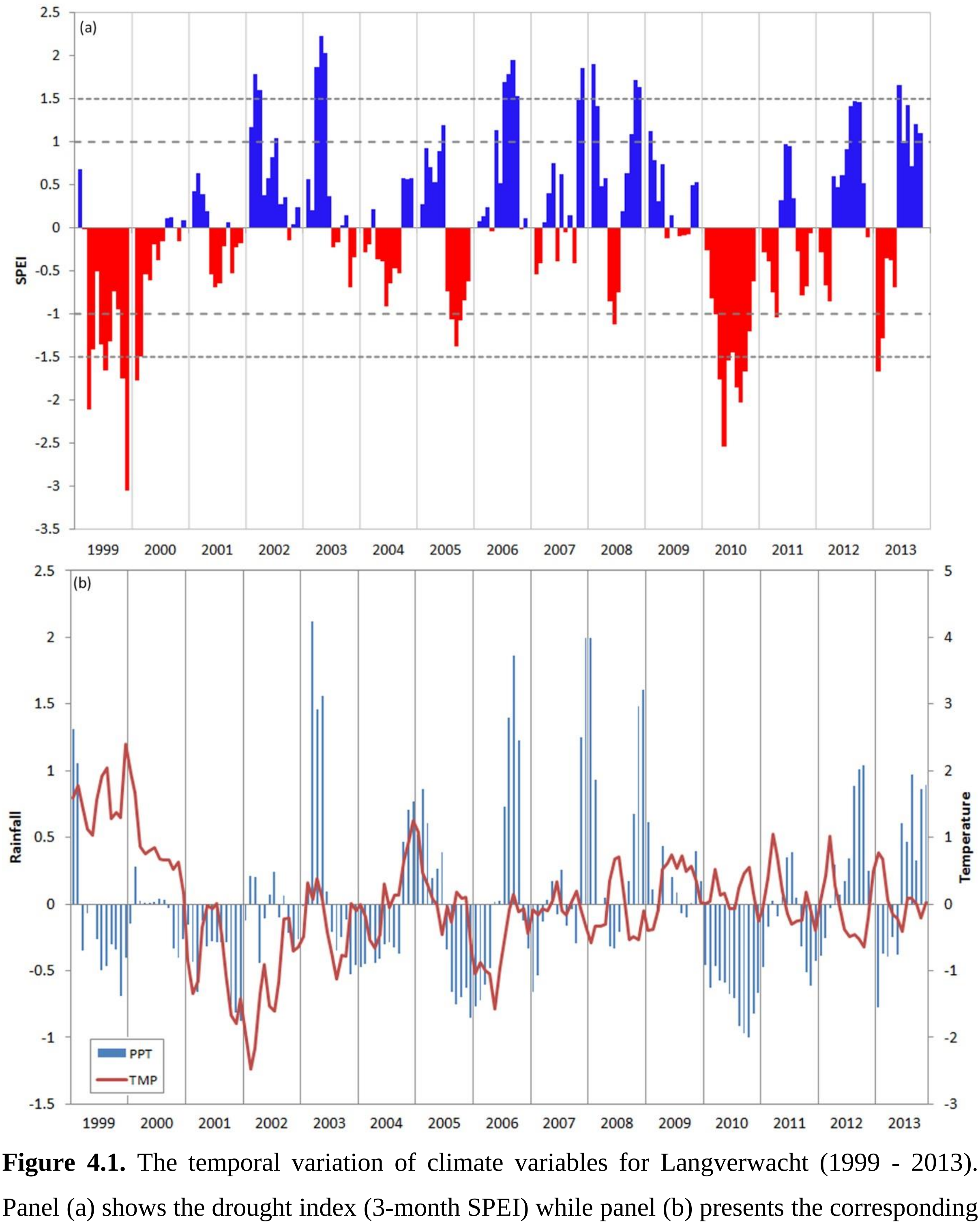

Figure 4.1. The temporal variation of climate variables for Langverwacht (1999 - 2013). Panel (a) shows the drought index (3-month SPEI) while panel (b) presents the corresponding rainfall anomalies (normalised with the mean value; bars) and temperature anomalies (^{o}C, line). In panel (a), the red bars (negative SPEI) indicate dry conditions while the blue bars (positive SPEI) indicate wet conditions; the thin and thick dash lines indicate the threshold for "moderate" and "severe" conditions, respectively, as indicated in Table 3.4.

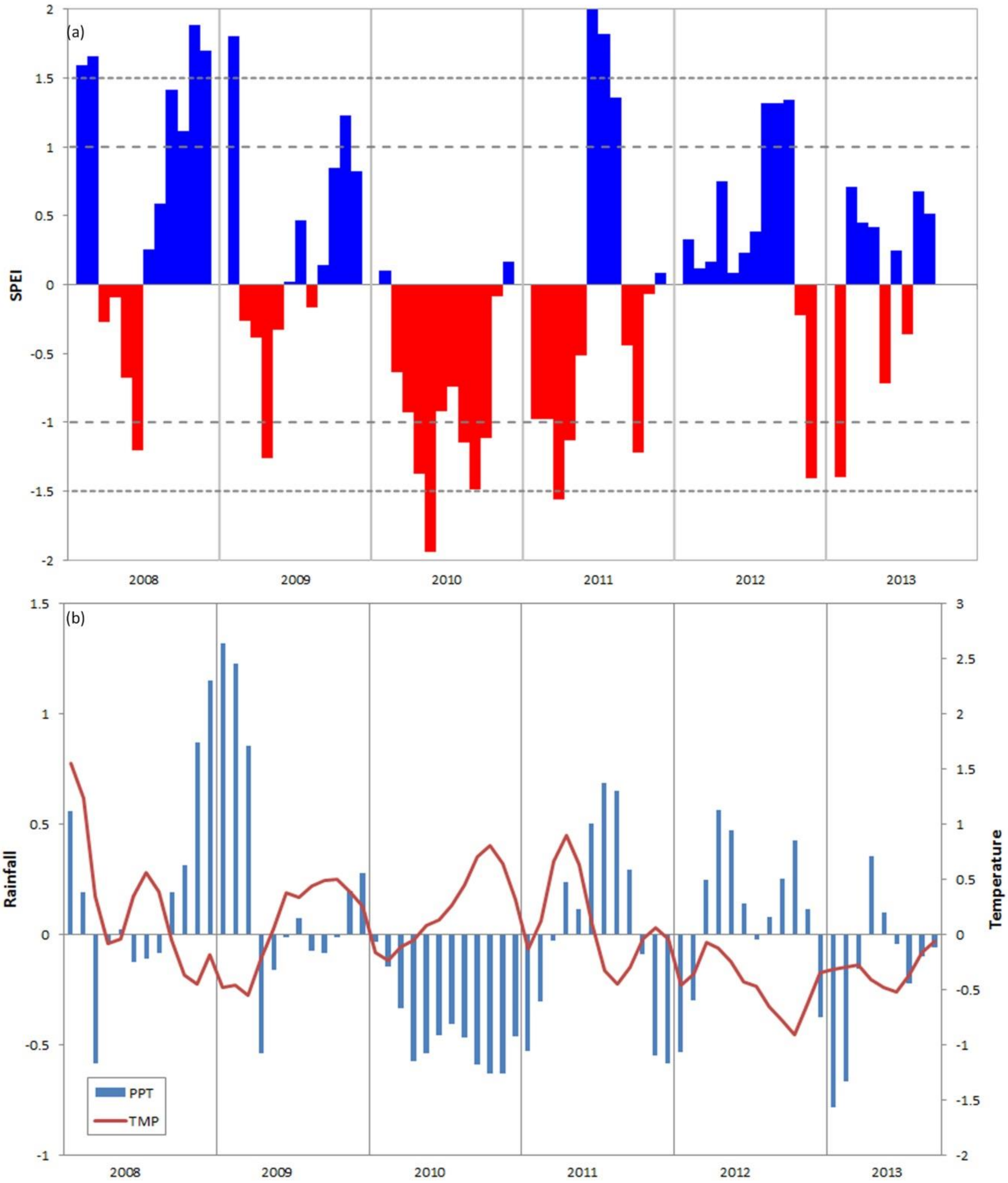

Figure 4.2. The temporal variation of climate variables for Vink Rivier (2008 - 2013). Panel (a) shows the drought index (3-month SPEI) while panel (b) presents the corresponding rainfall anomalies (normalised with the mean value; bars) and temperature anomalies (^{o}C, line). In panel (a), the red bars (negative SPEI) indicate dry conditions while the blue bars (positive SPEI) indicate wet conditions; the thin and thick dash lines indicate the threshold for “moderate” and “severe” conditions, respectively, as indicated in Table 3.4.

4.2 The temporal variation of grape yields at farm scale

The grape yields at Langverwacht and Vink Rivier vary from year to year and from one cultivar to another. Given that a decrease of more than 10 % in grape yield may have significant impacts on the income of a grape farmer (Cooper *et al*., 2010), we use 10 % as the threshold to identify substantial decrease (or increase) in the yield. At Langverwacht, within the period of 14 years (1999 – 2013), there were four periods with significant yield deficit (in 1999 – 2001, 2004 – 2005, 2009 and 2013) and two periods with significant yield surplus (2003 and 2006 – 2007) (Fig. 4.3). Out of the three cultivars at Langverwacht, Ruby Cabernet shows the highest variability in its yield; the standard deviation (σ) is about 21.5 ton/ha; the yield decreased by more than 85 % in 1999 and increased by more than 25 % in 2006 – 2008. Merlot and Chardonnay show the least variability (σ = 1.7 ton/ha and 2.8 ton/ha, respectively); the changes in the yields are within ±30 %. On the other hand, the Sauvignon Blanc (σ = 10.4 ton/ha) attained its maximum yield deficit in 2004 and 2009, and its maximum surplus in 2012.

At Vink Rivier, within the 6-year period (2008 – 2013), there is a period of significant deficit (2009 – 2011) and a period of significant surplus (2012). The cultivars (Shiraz and Colombar) exhibit a similar pattern in the yield variability (σ = 10.3 ton/ha and σ = 9.1 ton/ha, respectively), attaining their maximum yield deficit (about 65 % and 25 % decreases, respectively) in 2011 and their maximum surplus (87 % and 53 %, respectively) in 2012. There are some agreements in the grape yield variability at the two stations. For instance, both stations report significant deficit in 2009. Nevertheless, the sign yield anomalies do not always agree at both stations. For example, while Langverwacht reports deficit grape yields in 2008, Vink Rivier reports surpluses. While the discrepancies may be owing to the different averaging period of the data, it may also be owing to difference in management and soil type.

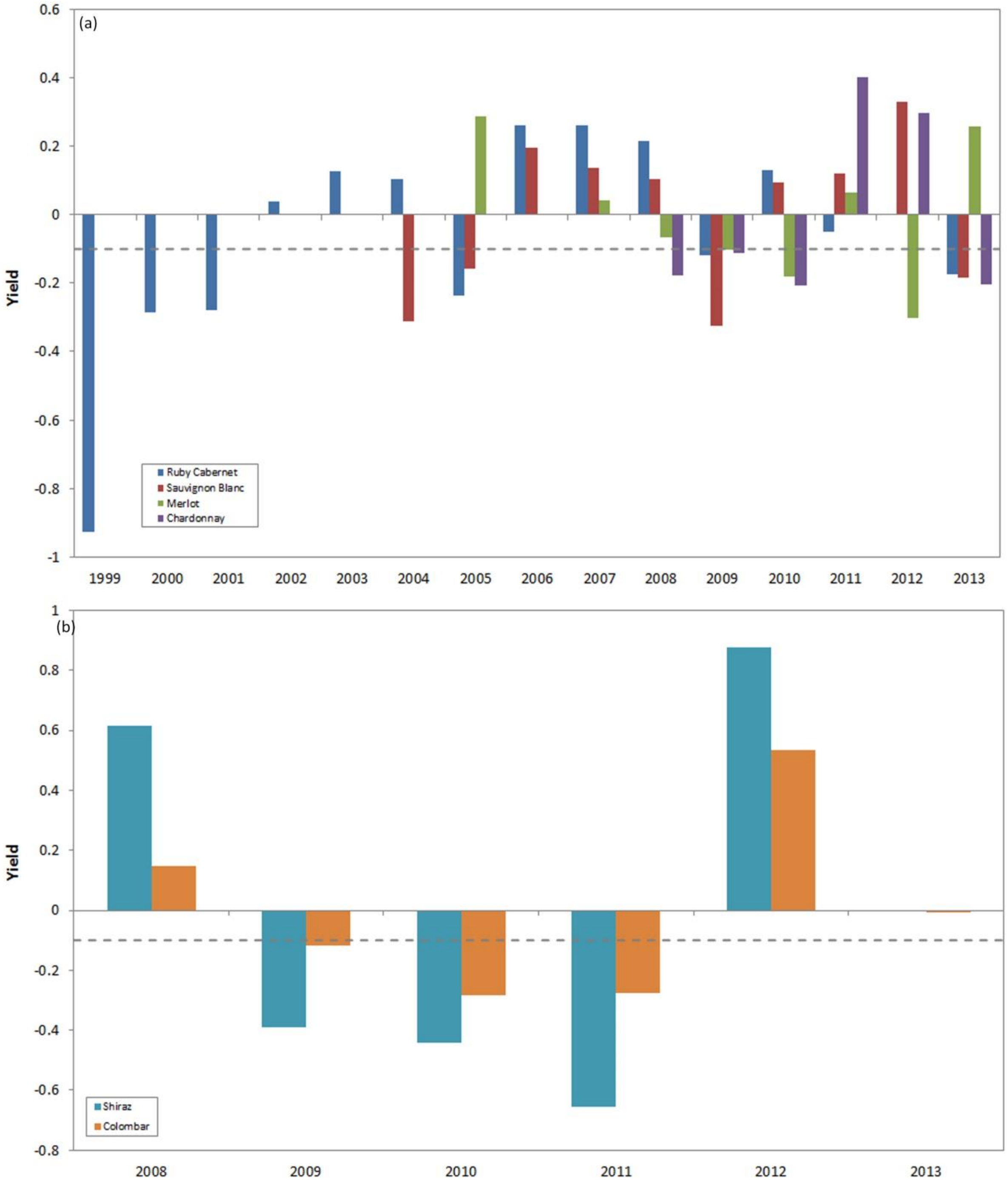

Figure 4.3. The inter-annual variation of grape yield (normalised anomalies) for cultivars at (a) Langverwacht and (b) Vink Rivier. The dotted line indicates the 10% change, which is used as a threshold for a significant change in the study.

4.3 Relationship between grape yields and climate variables at farm scale

Table 4.1 shows that, at each farm, the sensitivity of the grape yields to the climate variables (temperature, rainfall and drought) varies with seasons (*i.e*. phenological stages). Some grape yields show a significant correlation with temperature. For instance, Ruby Cabernet shows significant negative correlations with temperature in all seasons, except in SON (*i.e.* r = -0.5, -0.6, and -0.5 in DJF, MAM and JJA, respectively), Sauvignon Blanc shows a significant correlation with temperature in JJA (r = -0.6) and SON (r = -0.7), while Shiraz, Colombar and Chardonnay only show a significant correlation with temperature in JJA (r = -0.5, -0.6, and -0.7, respectively). However, Merlot does not show any significant correlation with temperature in season. The general negative correlation between yield and seasonal temperature found in this study is consistent with some previous studies (*e.g.* Ramos and Martinez-Casasnovas, 2010a). All cultivars (except Merlot) show a strong negative correlation with temperature in JJA. This could be as a result of the grapevines' ability to achieve the optimal number of chill units during dormancy, when there are lower temperatures. If the temperatures increase and are too high during dormancy, then the grapevines will not achieve the required amount of chill units and thus may break dormancy and bud too early in the season. This may lead to earlier ripening as well as the inability to achieve bloom (Webb *et al.*, 2007; Lavee and May, 1997). Similarly, the increase in temperature associated with drought during this stage can be explained by the theory that cold days during winter control (kill) grape diseases. It implies that, in a milder winter, as a result of warmer temperatures, (with temperatures not cool enough to kill off diseases), there will be a potential decrease in the grape yields (Jones *et al.*, 2005). The high negative correlation during DJF and MAM (ripening and harvest to early dormancy) disagrees with studies such as Ramos and Martinez-Casasnovas (2010b) or Bruwer (2010) that show that grapevines require drier conditions at veraison.

Table 4.1. The coefficient of correlation (r) between observed yields and climate variables (temperature, rainfall, and drought index) for different seasons (DJF, MAM, JJA and SON). The significant vales (r> 0.5) are in bold.

	Temperature				Rainfall				Drought Index (SPEI)			
Cultivar	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Shiraz	-0.2	-0.2	**-0.5**	-0.2	**0.5**	0.3	**0.7**	-0.3	**0.7**	**0.5**	**0.7**	-0.2
Colombar	-0.2	-0.4	**-0.6**	-0.3	0.3	**0.5**	**0.7**	-0.3	**0.5**	**0.6**	**0.7**	-0.3
Ruby Cabernet	**-0.5**	**-0.6**	**-0.5**	-0.2	**-0.5**	0.1	0.2	-0.1	0.1	0.2	0.3	0.1
Sauvignon Blanc	-0.1	-0.2	**-0.6**	**-0.7**	-0.2	0.2	0	**-0.5**	-0.2	0.2	-0.1	-0.4
Merlot	0.3	-0.1	-0.1	0.1	0.3	0.2	0.1	0.1	0	0.3	0	0
Chardonnay	0.4	-0.2	**-0.7**	-0.2	-0.2	**0.8**	**-0.6**	**-0.8**	-0.2	**0.7**	**-0.6**	**-0.9**

The high correlations during SON could be associated with the grapevines' moisture requirement during the early stages of growth. High temperatures during early growth may result in soil moisture loss (through enhanced evaporation), which, in turn, could reduce the yield (Malheiro *et al*., 2010). The high correlations tend to be more during JJA than the other seasons, suggesting that the grapevines are most sensitive to temperature during winter.

The grape yields show significant correlation with rainfall in some seasons and no correlation in other seasons. For instance, Chardonnay shows strong correlations with rainfall in all seasons, except in DJF (r = 0.8, -0.6 and -0.8 in MAM, JJA and SON, respectively) (Fig. 4.1). Shiraz shows a significant correlation with rainfall in DJF (r = 0.5) and JJA (r =0.7), and Colombar in MAM (r = 0.5) and JJA (r = 0.7). Ruby Cabernet and Sauvignon Blanc show high correlation with rainfall in DJF (-0.5) and SON (r = -0.5), respectively; while Merlot shows no significant correlation with rainfall in any season.

Unlike the correlations with temperature, there is no overall agreement between the cultivar yields and seasonal rainfall; some cultivars show positive correlations (*i.e*., r = 0.8), others show negative correlations (*i.e*., r = -0.8) (Fig 4.1). While two cultivars (Colombar and Chardonnay) agree on a positive correlation between the yield and rainfall in MAM, two cultivars (Shiraz and Colombar) agree on a positive correlation between the yield and rainfall in JJA, and two cultivars (Sauvignon Blanc and Chardonnay) agree on a negative correlation between the yield and rainfall in SON. The high negative correlation between yield and rainfall during SON disagrees with studies by Malheiro *et al*. (2010), which show that ample soil moisture (through rainfall and/or irrigation) during growth is beneficial to yields. The positive coherence between yield and rainfall during DJF and MAM could be explained by grapevines still requiring soil moisture at this stage; therefore, insufficient water for irrigation and low soil moisture during this stage may reduce the yields. High correlations during JJA (dormancy) could be associated with soil moisture and availability of water in the dams for irrigation during the next growth stages. Consequently, with a wetter winter, more water is available for the next growth season; thus, there is sufficient water to optimise the grape growth and increase the yield. Similarly, a decrease in rainfall as a result of drought during this stage will result in less available water for irrigation, as well as lower soil water at the start of the growth stages, causing a yield deficit.

Only three cultivars (Shiraz, Colombar and Chardonnay) show significant correlations between yields and the seasonal drought index. While Shiraz and Colombar yields show a significant correlation in DJF (r = 0.7 and 0.5, respectively), MAM (r = 0.5 and 0.6, respectively), and JJA (r = 0.7), Chardonnay shows the significant correlation in MAM (r = 0.7), JJA (r = -0.6) and SON (r = -0.9). Hence, the three cultivars agree on a positive correlation between yields and drought index in MAM.

In most cases, the strong correlation between the yield and drought index may be linked to the influence of rainfall and temperature on the yields. For example, with Shiraz and Colombar, the positive correlation between yields and drought index in DJF, MAM and JJA may be linked to the positive correlation between yield and rainfall and the negative correlation between yield and temperature in the seasons. The same is true for Chardonnay in MAM. However, there are cases where the significant correlation between the yield and drought index only agree with the influence of rainfall. In addition, there are cases where significant correlation between yield and temperature and between yield and rainfall does not produce any correlation between the yield and drought index. Nevertheless, a comparison of Figs. 4.1 – 4.3 show that a significant yield deficit occurs when the drought index is at least moderate, while a significant yield surplus occurs when the drought index is at least moderate wet conditions. For instance, the yield deficits at Langverwacht in 1999 – 2001 and at Vink Rivier in 2010 – 2011 coincide with the moderate drought that occurred during these periods, while yield surpluses (in 2006 – 2007 and 2012, respectively) coincide with at least moderate wet conditions in those years.

Chapter 5: Results and Discussion (2) - Drought and Grape Yield at District Scale

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5.1 Temporal variability of drought index at district scale

The temporal variation of SPEI at Robertson, Olifants River and Stellenbosch districts shows that the three districts have observed moderate and severe droughts in the past few years (1984 – 2009) (Figs. 4, 5 and 6, respectively). At Robertson (Fig. 5.1), there have been four major dry periods (1990, 1993, 1999 – 2000 and 2009) and four minor dry periods (1986, 2003, 2004 – 2005 and 2008) consisting of at least moderate drought. The major dry periods lasted more than 16 months and include moderate droughts (SPEI ≤ -1.0) for seven months and severe drought (SPEI ≤ -1.5) for nine months. The minor drought periods lasted more than 16 months and include moderate droughts for 12 months and severe drought for four months. Similarly the district has experienced intermittent wet conditions, which include four major wet periods (1985, 1989 – 1990, 1996 – 1997 and 2001) and three minor wet periods (1991 – 1992, 1995 and 2004). The major wet periods lasted for more than two years and include moderate wet (SPEI ≥ 1.0) conditions for 10 months and severe wet conditions (SPEI ≥ 1.5) for 13 months.

At Olifants River (Fig. 5.2), there were four major dry periods (around 1997, 1999 – 2000, 2003 and 2004 – 2005) and four minor periods (in 1984, 1993, 1995 and 2009) with at least moderate droughts. The four major dry periods lasted for more than two years, featuring moderate droughts for almost a year and severe drought for 15 months. The four minor dry periods lasted for 11 months and featured moderate droughts in about seven months and severe drought for four months. However, the district also experienced intermittent wet conditions with moderate wet to severe wet periods. The moderate wet conditions lasted for three months in 1987, five months in 1996 and three months in 2001.

Lastly, at Stellenbosch (Fig 5.3), there were five major dry periods (around 1993, 1997, 1999 – 2000, 2003 and 2009) and two minor periods (in 1985 – 1986 and 2005 – 2006) with at least moderate droughts. The five major dry periods lasted for more than two years, featuring moderate droughts for over a year and severe drought for 10 months. The two minor dry periods lasted for 13 months and feature moderate droughts in about 11 months and severe drought for two months. However, the district also experienced intermittent wet conditions with moderate wet to severe wet periods. The moderate wet conditions lasted for two months in 1987, three months in 1989, four months in 1996 and three months in 2001.

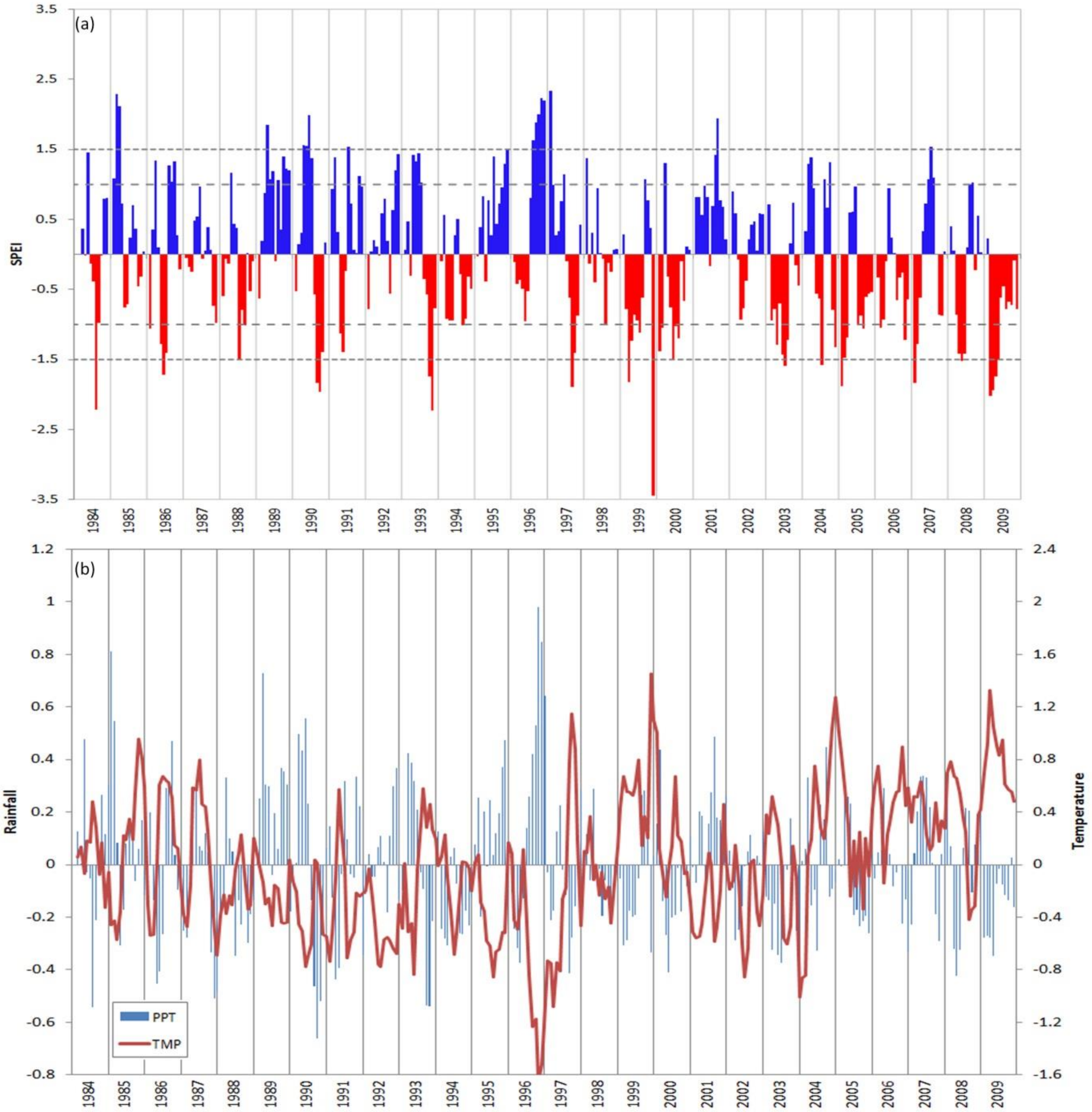

Figure 5.1. The temporal variation of climate variables for Robertson District (1984 - 2009). Panel (a) shows the drought index (3-month SPEI) while panel (b) presents the corresponding rainfall anomalies (normalised with the mean value; bars) and temperature anomalies (^{o}C, line). In panel (a), the red bars (negative SPEI) indicate dry conditions while the blue bars (positive SPEI) indicate wet conditions; the thin and thick dash lines indicate the threshold for “moderate” and “severe” conditions, respectively, as indicated in Table 3.4.

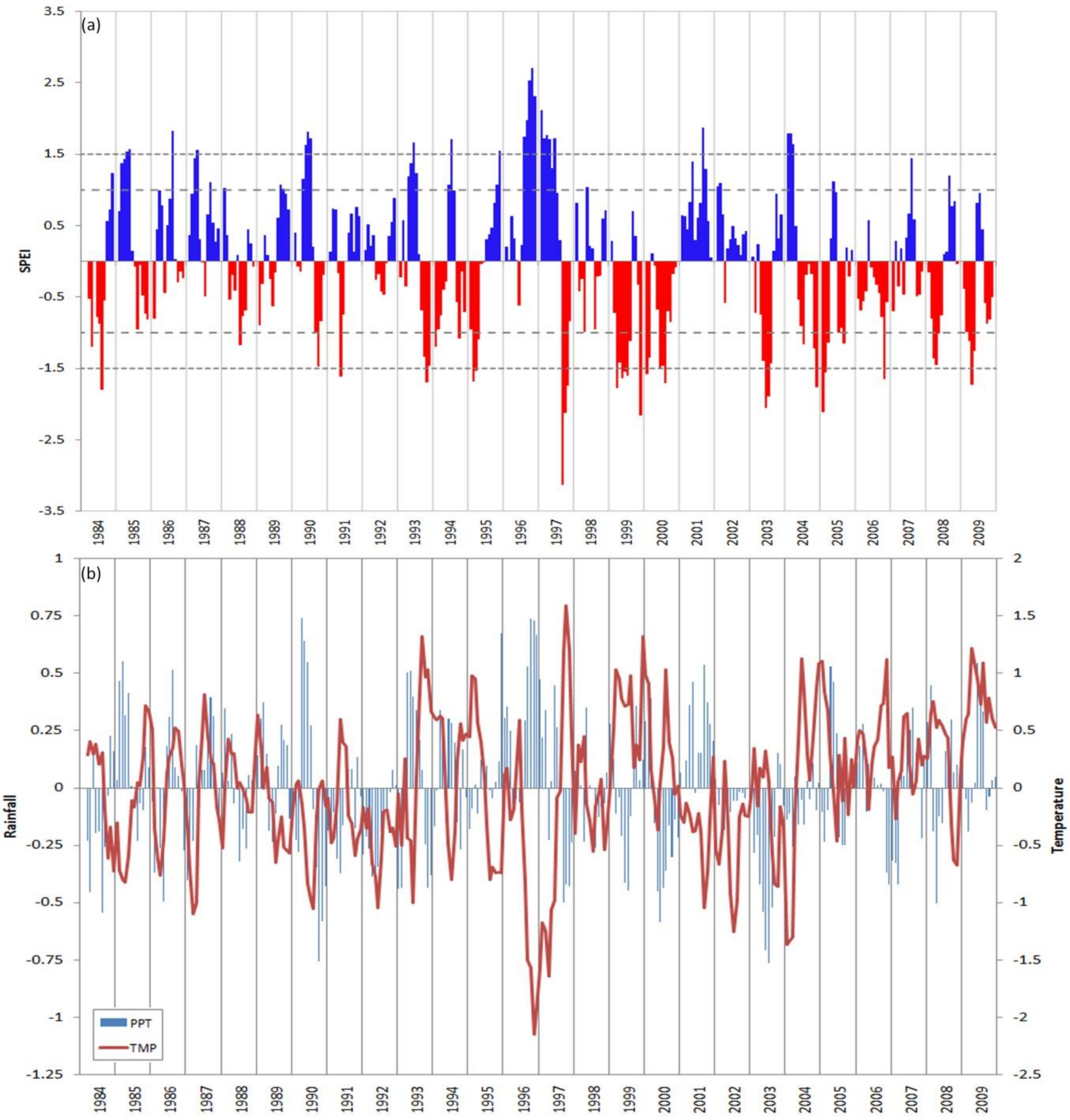

Figure 5.2. The temporal variation of climate variables for Olifants River District (1984 - 2009). Panel (a) shows the drought index (3-month SPEI) while panel (b) presents the corresponding rainfall anomalies (normalised with the mean value; bars) and temperature anomalies (^{o}C, line). In panel (a), the red bars (negative SPEI) indicate dry conditions while the blue bars (positive SPEI) indicate wet conditions; the thin and thick dash lines indicate the threshold for “moderate” and “severe” conditions, respectively, as indicated in Table 3.4.

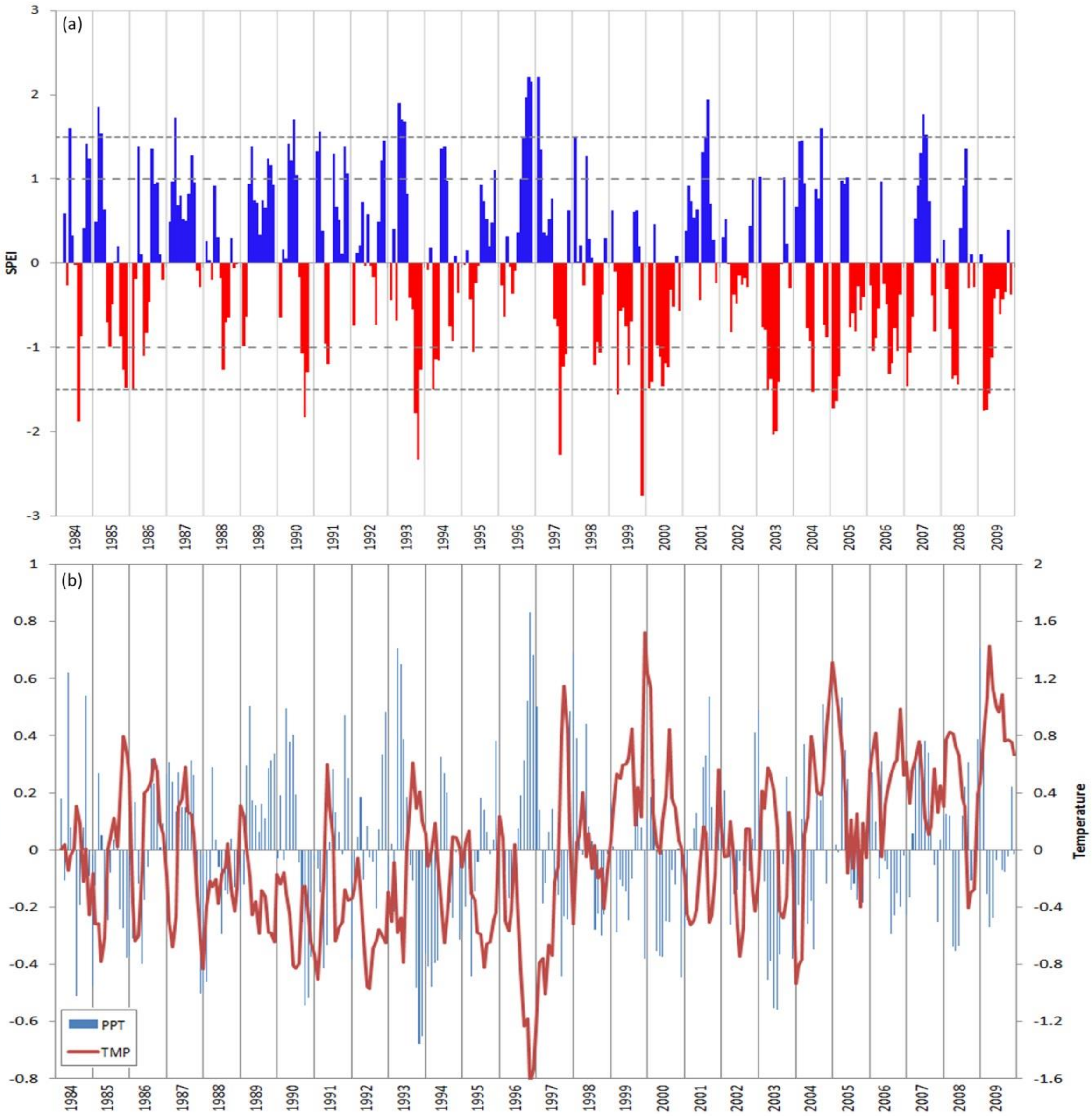

Figure 5.3. The temporal variation of climate variables for Stellenbosch District (1984 - 2009). Panel (a) shows the drought index (3-month SPEI) while panel (b) presents the corresponding rainfall anomalies (normalised with the mean value; bars) and temperature anomalies (^{o}C, line). In panel (a), the red bars (negative SPEI) indicate dry conditions while the blue bars (positive SPEI) indicate wet conditions; the thin and thick dash lines indicate the threshold for "moderate" and "severe" conditions, respectively, as indicated in Table 3.4.

Similar to that of farm scale, the district scale drought conditions are associated with negative anomalies in rainfall and positive anomalies in temperature, while wet conditions are associated with positive anomalies in rainfall and negative anomalies in temperature. For instance, in all three districts, the drought of 2000 is owing to deficit rainfall (around 40% at Robertson and Stellenbosch, and 50% at Olifants River) and surplus temperature (around 1°C at Robertson and Olifants River, and 0.8°C at Stellenbosch). A negative rainfall anomaly with positive temperature seems to produce more severe drought than with negative temperature anomalies. For instance at Robertson (Fig. 5.1), though the rainfall deficit was higher in 1990 (about 60%) than in 1999 (about 20%), the drought was more severe in 1999 than in 1990, because the temperature was higher (hence evaporation). This shows a similar relationship with that of drought at the Langverwacht station, which suggests that the drought events are captured at both farm and district scales. The Langverwacht drought events of 1999 and 2005 are reflected in the Robertson SPEI; however the district drought in 2009 is not reflected at Langverwacht. This could be as a result of scale, as some areas within the district may not have experienced the 2009 drought, as they are located in a slightly wetter area of the district. Stations that are near mountains (such as the Langeberg in Robertson) may receive more rainfall than stations located in the flatter areas in the district owing to orographic forcing.

Both drought and wet conditions are reflected at all three districts, specifically during 1999 – 2000 and 2009; and 1996 and 2001, respectively. This suggests that severe drought events occur over the entire Western Cape; however the moderate droughts may occur at different periods throughout the individual districts. As such, the SPEI approach is able to capture droughts at district as well as farm scale. It is important to note that using single or two stations to extrapolate drought occurrences and impacts over a province may not be accurate as those stations may be experiencing wet conditions while the other stations as well as districts may be experiencing drought. Therefore, since district scale captures a similar drought pattern to farm scale, using a district-wide analysis may be more accurate than using a single weather station to identify the relationship between drought and yield in western South Africa.

5.2 Grape Yield groups for Robertson, Olifants River and Stellenbosch

Using a district scale to analyse the impact of drought on grape yields allows for a better general understanding of this relationship. Where specific farms may show that their yields are reduced by drought events, the average over the district may differ, as some farms may have access to greater constant supplies of water, which will enable them to counter the effects of drought. As such, it is necessary to cluster the cultivars planted in each district, which will then cover a wide range of yields instead of just a few. Here we compare the inter-annual variability of the grape yields with that of grape yield groups (obtained from the PCA) to show how well the yields are coupled under each group, and how well the group reproduces the inter-annual variability of the grape yields it couples. In some cases, some cultivars are significantly coupled with opposite loadings under the same group. This negative coupling may be owing to differences in management practices on the grapevine; for instance, differences in irrigation and fertilizer applications could produce different yields among the cultivars. It could also be owing to phenological differences. However, the focus of this study is on the cultivars with positive loadings in the group. In addition, we discuss the variation of the coupling among the districts.

With Robertson’s grape yields (Table 5.1), the cultivars have three significant groups (*i.e.* the three leading principal factors of the PCA; RPF1, RPF2, and RPF3). These three groups (principal factors) jointly explain 61.78 % of the total variance in the grape yield dataset: RPF1 explains 20.87 % and contains six cultivars (*i.e.* loadings > 0.5); RPF2 explains 20.26% and contains six cultivars, while RPF3 explains 20.58 % and contains five cultivars. RPF1 shows its highest loading (0.91) for Colombar, the significant positive loadings for four cultivars (Colombar, Chardonnay, Weldra and Chenin Blanc) and significant negative loadings for two cultivars (Raisin Blanc and Chenin Blanc).

In RPF1, Weldra has the highest yield (20 ton/ha) while Chardonnay has the lowest yield (7 ton/ha; Fig. 5.4). RPF2 shows its highest loading (0.88) for Ugni Blanc, with significant positive loadings for five cultivars (Raisin Blanc, Chenin Blanc, Pinot Noir, Muskadel, and Ugni Blanc) and significant negative loading for one cultivar (Pinotage). Raisin Blanc has the highest yields (24 ton/ha) and Pinot Noir the lowest (8 ton/ha). On the other hand, RPF3 shows its highest loading (0.86) for Chenel and significant positive loadings for five cultivars (Pinotage, Cabernet Sauvignon, Clairette Blanch, Shiraz, and Chenel). Clairette Blanch has the highest yield (23 ton/ha) and Cabernet Sauvignon the lowest (7 ton/ha). All the groups show negative values in 1984 – 1986.

While RPF2 and RPF3 show a decreasing trend in 1989 – 1998, RPF1 shows an increasing trend between 1984 – 1992 and no apparent change afterward. RPF3 shows a considerable positive trend in 2004 – 2009, when RPF1 and RPF2 show no trend. For all three groups (RPF1, RPF2 and RPF3), when there are positive anomalies for the yields, the principal factor scores are positive and when the anomalies are negative, the scores are negative. Thus the scores give a good representation of the inter-annual variability of the yields.

Table 5.1. The PCA loadings (rotated) for Robertson grape yields (14 cultivars). Significant loadings (>0.50) are in bold.

Cultivar	**RPF1**	**RPF2**	**RPF3**
Colombar	**0.91**	0.17	0.17
Chardonnay	**0.78**	-0.31	0.19
Weldra	**0.54**	0.05	-0.23
Sauvignon Blanc	**-0.50**	-0.05	-0.08
Raisin Blanc	**-0.57**	**0.65**	0.15
Chenin Blanc	**0.60**	**0.52**	-0.06
Pinot Noir	0.24	**0.70**	-0.25
Muskadel (red)	-0.02	**0.50**	-0.08
Ugni Blanc	0.04	**0.88**	0.14
Pinotage	0.19	**-0.50**	**0.76**
Cabernet Sauvignon	-0.32	-0.44	**0.54**
Clairette Blanch	0.20	0.08	**0.63**
Shiraz	-0.22	-0.18	**0.81**
Chenel	0.10	0.17	**0.86**
Explained Variance (%)	**20.87**	**20.26**	**20.58**

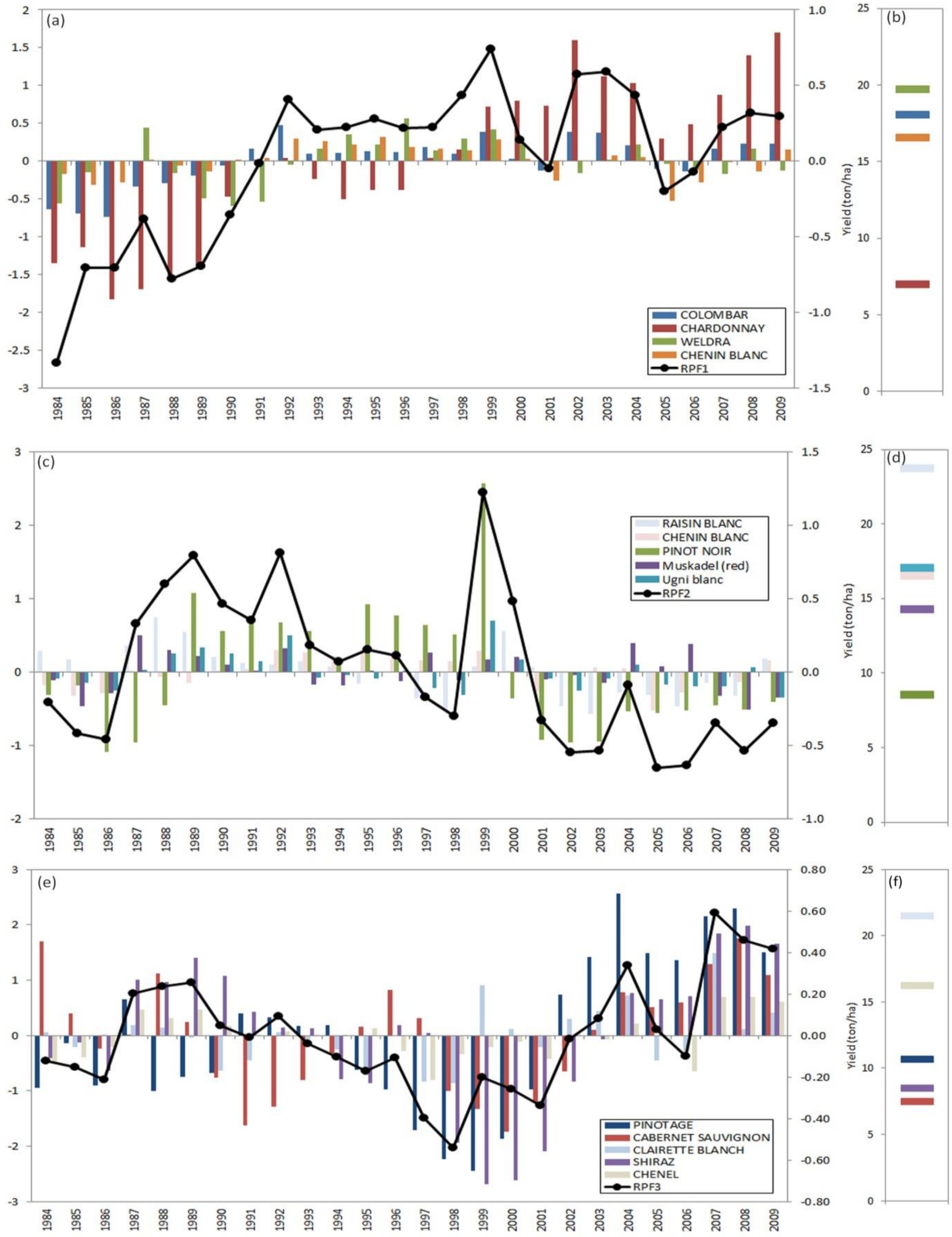

Figure 5.4. Grape (cultivars) yields and the PCA grouping (scores) of cultivars in Stellenbosch district. The left panels (a, c, and e) show the inter-annual variations (anomalies, bars) of the grape yields and the PCA scores (lines) for RPF1 (a), RPF2 (c) and RPF3 (e) in 1984 – 2009. The right panels (b, d and f) show the mean value of the yield, used in obtaining the anomalies. The yields are in ton/ha.

The PCA classified the cultivars in Olifants River into two significant groups (OPF1 and OPF2), which jointly explain 82.69 % of the total variance grape yield data (Table 5.2). The OPF1 explains 50.22 % and couples nine cultivars, while OGF2 explains 32.47 % and couples seven cultivars (Table 5.2). OPF1 shows its highest loading (0.92) for Chenin Blanc, significant positive loadings for seven cultivars (Chenel, Chenin Blanc, Colombar, Fernao Pries, Harslevelu, Semillon and Clairette Blanch) and significant negative loadings for two cultivars (Pinotage and Sauvignon Blanc); Clairette Blanch has the highest yield (26 ton/ha), while Semillon has the lowest yield (10 ton/ha; Fig. 5.5). OPF2 shows its highest loading (0.90) for Cabernet Sauvignon and Raisin Blanc, its significant positive loadings for four cultivars (Clairette Blanch, Cabernet Sauvignon, Raisin Blanc and Tinta Barocca) and its significant negative loading for three cultivars (Pinotage, Sauvignon Blanc and Bukettraube). Raisin Blanc has the highest yields (36 ton/ha) and Cabernet Sauvignon the lowest (4 ton/ha). The two groups (OPF1 and OPF2) have inter-annual variability and capture variation of their grape yield well (Fig. 5.5). In 1984 – 1989, OPF2 shows an increasing trend, while OPF1 shows a decreasing trend. In 1991 – 1994 there is a weak decreasing trend in OPF1, but a strong increasing trend in OPF2. While OPF1 shows no considerable change in 2004 – 2009, OPF2 shows a substantial positive trend, but with a drop in 2008 – 2009. Overall, the principal factor scores capture the trend of the yield anomalies throughout the period (1984 – 2009).

Table 5.2. The PCA loadings (rotated) for Olifants River grape yields (13 cultivars). Significant loadings (>0.50) are in bold.

Cultivar	OPF1	OPF2
Chenel	**0.73**	-0.12
Chenin Blanc	**0.92**	0.26
Colombar	**0.89**	0.36
Fernao Pires	**0.87**	0.35
Harslevelu	**0.87**	0.10
Semillon	**0.82**	0.41
Clairette Blanch	**0.59**	**0.64**
Pinotage	**-0.78**	**-0.50**
Sauvignon Blanc	**-0.79**	**-0.53**
Bukettraube	0.49	**-0.69**
Cabernet Sauvignon	0.21	**0.90**
Raisin Blanc	0.31	**0.90**
Tinta Barocca	0.49	**0.83**
Explained Variance (%)	**50.22**	**32.47**

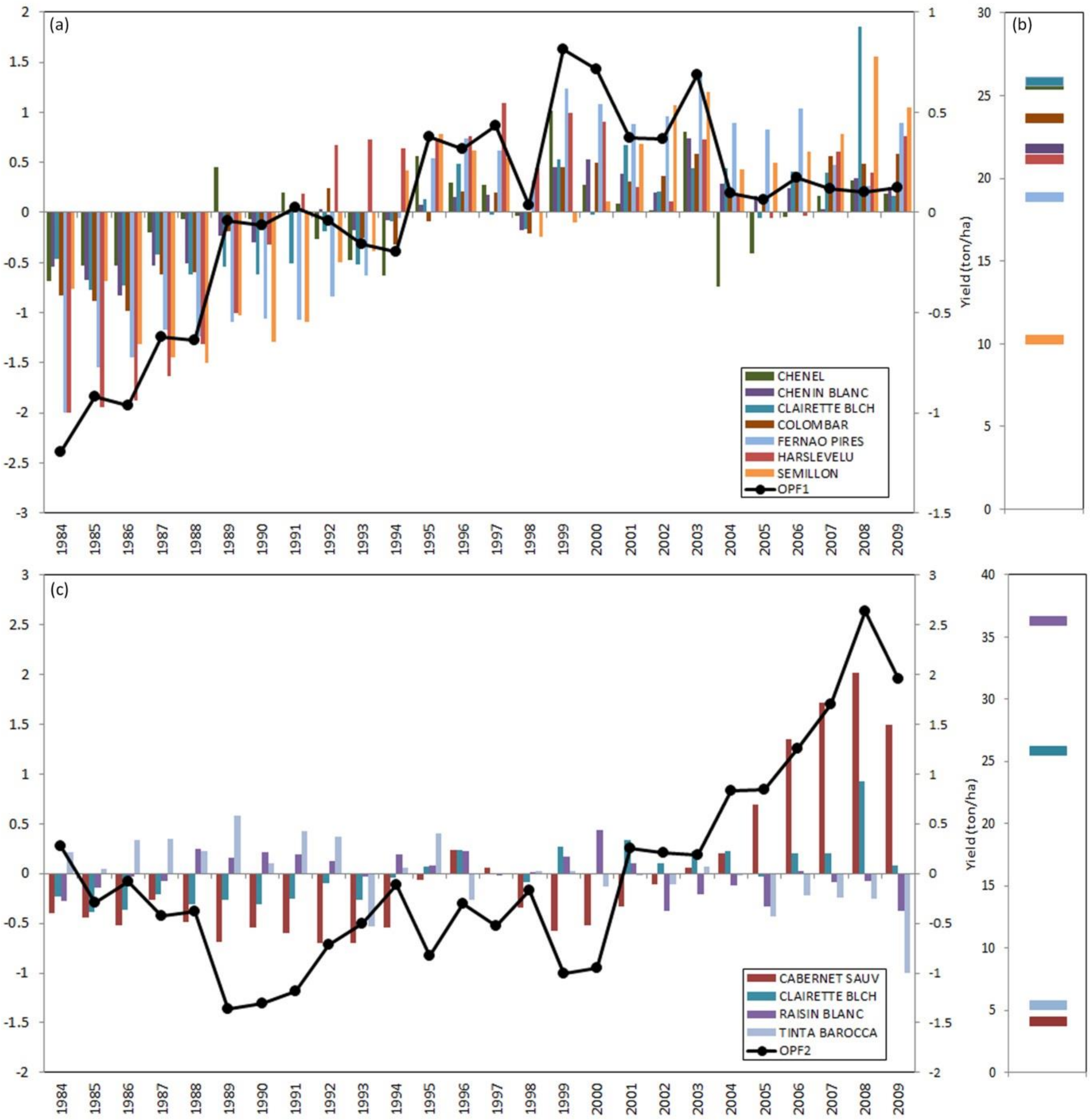

Figure 5.5. Grape (cultivars) yields and the PCA grouping (scores) of cultivars in Olifants River district. The left panels (a and c) show the inter-annual variations (anomalies, bars) of the grape yields and the PCA scores (lines) for OPF1 (a) and OPF2 (c) in 1984 – 2009. The right panels (b and d) show the mean value of the yield, used in obtaining the anomalies. The yields are in ton/ha.

The PCA classified Stellenbosch's grape yields (cultivars) into three significant groups (SPF1, SPF2, and SGP3) (Table 5.3). The loadings for these groups jointly explain 72.31 % of the total variance in the dataset, such that SPF1 explains 30.63 % of the variance and couples nine cultivars; SPF2 explains 20.81 % and couples seven cultivars, while SPF3 explains 20.87 % and couples five cultivars (Table 5.3). SPF1 shows its highest loading

(0.90) for Gewurztraminer, significant positive loadings for 10 cultivars (Chardonnay, Pinot Noir, Sauvignon Blanc, Gamay Noir, Gewurztraminer, Mario Muscat, Clairette Blanch, Merlot, Weisser Riesling and Colombar). In SPF1, Clairette Blanch has the highest yield (12 ton/ha; Fig 5.6), while Chardonnay has the lowest yield (4 ton/ha). SPF2 shows its highest loading (0.79) for Cabernet Sauvignon, significant positive loadings for six cultivars (Clairette Blanch, Merlot, Cabernet Sauvignon, Ruby Cabernet, Wyndruif Varia and Semillon) and the significant negative loading for one cultivar (Weisser Riesling). Wyndruif Varia has the highest yields (24 ton/ha) and Cabernet Sauvignon the lowest (5 ton/ha). On the other hand, SPF3 shows its highest loading (0.94) for Pinotage and significant positive loadings for five cultivars (Semillon, Carigan, Pinotage, Tinta Barocca and Colombar). Colombar has the highest yield (11 ton/ha) and Semillon the lowest (6 ton/ha). All three groups show negative values in 2002, as well as positive values from 2003 – 2009. From 1986 – 1990, both SPF1 and SPF3 show a positive trend, whereas SPF2 is negative. From 1991 – 1997, SPF1 shows no significant trend, whereas SPF2 shows a positive trend and SPF3 a negative trend. Lastly from 2003 – 2009, both SPF2 and SPF3 show a positive trend, whereas SPF1 shows a negative trend. For all three groups, the scores capture the trend of the yield anomalies (for the yields with positive loadings). As a result, the scores of SPF1, SPF2 and SPF3 in all three areas are good indices for the grape yields in their groups.

Table 5.3. The PCA loadings (rotated) for Stellenbosch grape yields (14 cultivars). Significant loadings (>0.50) are in bold.

Cultivar	**SPF1**	**SPF2**	**SPF3**
Chardonnay	**0.69**	0.43	-0.44
Pinot Noir	**0.78**	-0.04	0.06
Sauvignon Blanc	**0.81**	-0.38	-0.19
Gamay Noir	**0.69**	0.36	-0.41
Gewurztraminer	**0.90**	0.08	-0.03
Mario Muscat	**0.80**	-0.10	-0.35
Clairette Blanch	**0.52**	**0.52**	0.49
Merlot	**0.52**	**0.75**	-0.32
Weisser Riesling	**0.52**	**-0.70**	-0.05
Cabernet Sauvignon	0.01	**0.79**	-0.09
Ruby Cabernet	-0.29	**0.60**	-0.09
Wyndruif Varia	0.19	**0.59**	0.09
Semillon	-0.01	**0.63**	**0.57**
Carigan	-0.33	-0.06	**0.76**
Pinotage	-0.03	-0.05	**0.94**
Tinta Barocca	-0.06	-0.01	**0.76**
Colombar	**0.72**	0.06	**0.54**
Explained Variance (%)	**30.63**	**20.81**	**20.87**

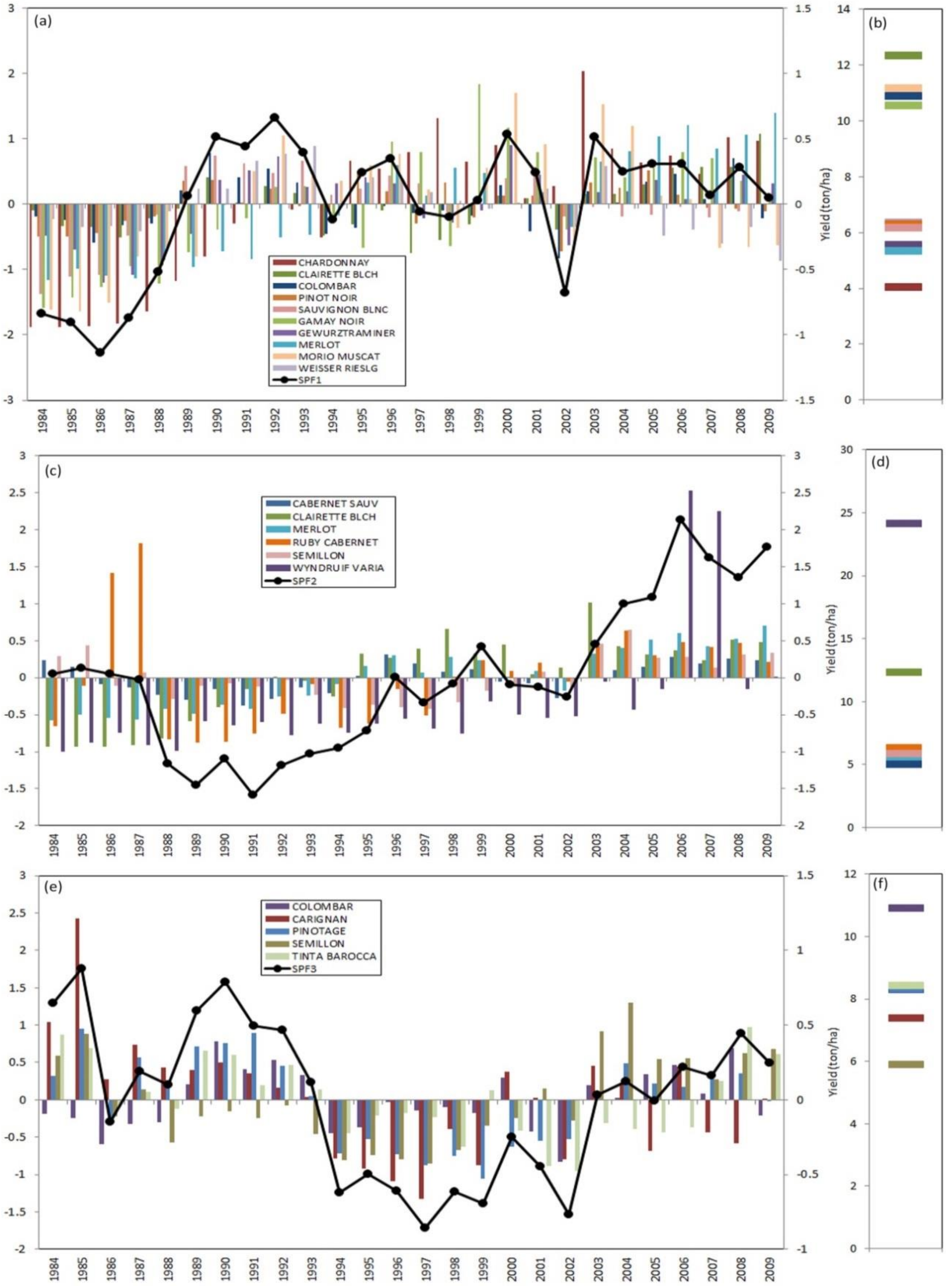

Figure 5.6. Grape (cultivars) yields and the PCA grouping (scores) of cultivars in Stellenbosch district. The left panels (a, c, and e) show the inter-annual variations (anomalies, bars) of the grape yields and the PCA scores (lines) for SPF1 (a), SPF2 (c) and SPF3 (e) in 1984 – 2009. The right panels (b, d and f) show the mean value of the yield, used in obtaining the anomalies. The yields are in ton/ha.

At Robertson (Fig. 5.4), within a period of 26 years (1984 – 2009), there were three periods of significant yield deficit (1984 – 1985, 2001 and 2006) and one period of yield surplus (1992) where all yields (RPF1 – RPF3) had the same sign. At Olifants River (Fig. 5.5), within a period of 26 years (1984 – 2009), there were two periods of significant yield deficit (1985 – 1990 and 1992 – 1994) and one period of significant yield surplus (2001 – 2006). At Stellenbosch (Fig. 5.6), within a period of 26 years (1984 – 2009), there were three periods of significant yield deficit (1994, 1997 – 1998 and 2002) and one period of significant yield surplus (2003 – 2009). Although the variation in yield differed between the districts, there were periods where there was consensus between some of the yields. For instance, both Robertson and Olifants River shared yield deficit during 1985 and surplus during 1992. Similarly Olifants River and Stellenbosch shared yield deficit during 1994 and yield surplus during 2003 – 2006. It was no surprise that there were no periods where variability at all three districts agreed, as different cultivars were present in each yield group and management practices will differ.

5.3 Relation between drought and yield at district scale

Tables (5.4 – 5.6) show that, at all districts, the sensitivity of the grape yields to the climate variables (temperature, rainfall and drought) varies with seasons (*i.e.* phenological stages). Some grape yields show a significant correlation with temperature. For instance, RPF1 shows a significant negative correlation with temperature in JJA (r = -0.5), RPF3 shows a significant positive correlation in MAM (r = 0.6), while SPF2 shows a positive correlation in DJF (r = 0.6) and MAM (r = 0.6). Alternatively, the grape yields from Olifants River show no significant correlation with temperature.

The grape yields show little significant correlation with rainfall in any of the seasons. Only Chardonnay (r = 0.5 in DJF) in Stellenbosch shows a significant positive correlation with rainfall. This is likely as a result of farms being able to apply additional irrigation during low rainfall periods. During low rainfall periods, the soil moisture will be reduced and then, depending on the season, the yields will either increase or decrease. For instance, a prolonged reduction in soil moisture from deficit rainfall during budding will reduce the yield. However, if the farms are able to apply additional irrigation to compensate for the reduction in rainfall, then the soil moisture will return to the optimal state and the yield may not significantly change. As a result, the influence of rainfall is lost through irrigation management.

Only cultivars from SPF2 show any significant correlation between yield and seasonal drought index. SPF2 shows a significant negative correlation (r = -0.5) during DJF. Similarly Clairette Blanch and Merlot show significant negative correlations (r = -0.6 and r = -0.5, respectively) during DJF. It is no surprise that SPF2 has a significant correlation, as both Clairette Blanch and Merlot are cultivars in that yield group. The negative correlation between yield and drought index for SPF2 is associated with an increase in temperature. Yield deficits that occur during 1984 – 1985, 1994 and 1999 – 2001 correspond with drought, while surpluses that occur during 1989 – 1990, 1996 and 2001 correspond with wet conditions. This, however, is not reflected in the correlation between district yield and drought index. This could be as a result of irrigation management, as farmers in the district could have been able to mitigate some of the negative effects of drought but not eliminate them completely. This would still result in a yield deficit, as the impact of drought was not completely removed, but the irrigation management was enough to lower the correlation.

The influence of drought on the observed yields (individual farm) showed that yields are sensitive to drought throughout the grapevine's growth, specifically during autumn and winter. Since the SPEI was able to capture drought at both farm and district scales (*i.e*. the droughts of 1999 and 2005), we would expect to identify a similar relationship between drought and yield as observed. This, however, is not evident. For example, Shiraz and Colombar (farm scale) are sensitive to drought during all seasons (excluding SON), while no cultivars show any significant correlation at district scale. This may be explained by the following: some farms are able to mitigate drought effects by applying additional irrigation, while others are not. Thus, there are likely to be more farmers who are able to mitigate drought impacts, which will lower the correlation between drought and yield. Localised farm scale results are just a small part of what is occurring at a specific area of a district and should not be used to infer impacts outside of the scale of their farms. Also the impact of drought on yields tends not to be a major problem at district scale as opposed to farm scale. Therefore, it appears that irrigation management is able to mitigate the impact of drought at district scale.

Table 5.4. The coefficient of correlation (r) between district yields and climate variables (temperature, rainfall, and drought index) at different seasons (DJF, MAM, JJA and SON) at Robertson. The significant vales (r> 0.5) are in bold.

	Temperature				Rainfall				Drought Index (SPEI)			
Cultivar	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
CABERNET SAUVIGNON	0.2	0.3	0.0	0.1	-0.1	0.0	0.1	-0.1	-0.2	-0.1	0.2	-0.1
COLOMBAR	0.2	0.2	**-0.5**	-0.4	-0.3	-0.1	0.2	0.0	-0.3	-0.1	0.2	0.1
CLAIRETTE BLANCH	0.2	**0.6**	0.2	0.2	-0.3	-0.2	-0.1	-0.2	-0.3	-0.3	-0.1	-0.1
PINOT NOIR	0.0	-0.2	**-0.5**	-0.4	0.0	0.1	-0.2	0.0	0.1	0.1	-0.2	0.1
MUSKADEL(ROOI)	-0.2	-0.2	-0.2	-0.3	-0.4	0.4	0.1	0.1	0.0	0.4	0.1	0.1
PINOTAGE	0.1	**0.5**	0.0	0.3	0.0	-0.1	0.1	-0.3	-0.2	-0.2	0.1	-0.2
UGNI BLANC	0.0	-0.1	-0.1	-0.3	0.0	0.0	-0.2	-0.1	0.0	0.0	-0.2	0.0
SAUVIGNON BLANC	0.2	0.0	-0.4	-0.3	-0.4	0.2	0.2	-0.1	-0.3	0.1	0.2	0.0
SHIRAZ	0.0	0.3	-0.1	0.0	-0.2	0.1	0.3	-0.1	-0.1	0.1	0.3	-0.1
CHENIN BLANC	-0.2	-0.1	**-0.5**	-0.4	-0.3	-0.1	0.1	0.2	0.0	-0.1	0.1	0.2
CHENEL	0.2	**0.6**	0.3	0.2	-0.2	0.0	0.3	-0.4	-0.3	-0.1	0.2	-0.3
CHARDONNAY	0.4	0.4	-0.1	-0.1	-0.1	-0.2	0.1	0.0	-0.4	-0.3	0.1	0.0
RAISIN BLANC	-0.1	-0.1	0.4	-0.1	0.0	0.0	-0.1	-0.1	0.0	0.0	-0.2	0.0
WELDRA	0.1	0.0	-0.1	0.1	-0.1	-0.2	0.0	0.1	-0.1	-0.2	0.0	0.1
RPF1	0.2	0.2	**-0.5**	-0.2	0.2	-0.2	-0.2	0.1	-0.2	-0.2	0.1	0.1
RPF2	-0.2	-0.2	-0.1	-0.4	0.3	0.2	-0.1	0.2	0.0	0.1	-0.1	0.1
RPF3	0.2	**0.6**	0.1	0.1	0.1	0.0	0.3	-0.1	-0.3	-0.1	0.2	-0.2

Table 5.5. The coefficient of correlation (r) between district yields and climate variables (temperature, rainfall, and drought index) at different seasons (DJF, MAM, JJA and SON) at Olifants River. The significant vales (r> 0.5) are in bold.

	Temperature				Rainfall				Drought Index (SPEI)			
Cultivar	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
BUKETTRAUBE	0.4	0.4	0.4	0.4	0.0	0.0	-0.2	0.2	0.0	0.1	-0.1	0.2
CABERNET SAUVIGNON	-0.4	-0.3	-0.4	-0.4	0.1	0.1	0.2	-0.1	-0.3	-0.2	0.2	-0.2
CHENEL	-0.1	-0.1	-0.1	-0.2	0.3	-0.3	0.2	0.0	-0.4	**-0.5**	0.2	0.2
CHENIN BLANC	-0.1	-0.1	-0.1	-0.1	0.1	-0.2	-0.1	-0.1	-0.4	-0.4	0.0	0.1
CLAIRETTE BLANCH	0.0	0.0	0.0	-0.1	0.2	-0.1	0.1	-0.2	-0.3	-0.3	0.1	-0.1
COLOMBAR	-0.2	-0.2	-0.2	-0.3	0.1	-0.2	0.0	-0.1	-0.3	-0.4	0.0	0.1
FERNAO PIRES	-0.2	-0.2	-0.2	-0.2	0.1	-0.1	-0.1	0.0	-0.4	-0.2	-0.1	0.0
HARSLEVELU	-0.1	-0.2	-0.2	-0.2	0.0	-0.1	0.1	-0.1	-0.3	-0.2	0.2	0.1
PINOTAGE	0.2	0.2	0.2	0.2	-0.1	0.0	0.1	0.0	0.3	0.1	0.1	0.1
RAISIN BLANC	-0.4	-0.3	-0.4	-0.4	-0.1	0.0	0.0	-0.2	-0.2	-0.3	0.0	-0.2
SAUVIGNON BLANC	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.1	0.3	0.1	0.0	0.1
SEMILLON	-0.2	-0.2	-0.2	-0.2	0.1	0.0	0.0	0.0	-0.3	-0.2	0.1	0.0
TINTA BAROCCA	-0.3	-0.3	-0.3	-0.3	0.0	0.0	0.0	-0.1	-0.2	-0.3	0.0	-0.1
OPF1	0.3	0.2	-0.2	-0.2	0.1	-0.2	0.0	0.0	-0.4	-0.3	0.0	0.2
OPF2	0.1	0.4	0.2	0.2	0.0	0.1	0.1	-0.2	-0.1	-0.2	0.0	-0.3

Table 5.6. The coefficient of correlation (r) between district yields and climate variables (temperature, rainfall, and drought index) at different seasons (DJF, MAM, JJA and SON) at Stellenbosch. The significant vales (r> 0.5) are in bold.

	Temperature				Rainfall				Drought Index (SPEI)			
Cultivar	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
CABERNET SAUVIGNON	0.4	0.3	0.0	0.2	0.3	0.0	-0.1	-0.1	-0.3	0.0	-0.1	0.1
CHARDONNAY	**0.5**	0.4	-0.2	0.0	**0.5**	-0.1	0.0	0.1	-0.4	-0.1	0.0	0.0
CLAIRETTE BLANCH	**0.5**	**0.5**	0.1	0.1	0.2	0.1	0.0	0.0	**-0.6**	0.0	0.0	0.0
COLOMBAR	0.3	0.1	-0.3	-0.1	0.3	0.2	0.0	-0.1	-0.3	0.2	0.0	0.1
CARIGNAN	-0.2	-0.1	0.2	0.1	0.0	-0.1	-0.4	-0.2	0.2	0.0	-0.4	0.2
PINOT NOIR	0.3	0.0	-0.3	0.1	0.1	0.3	-0.1	0.1	-0.4	0.3	-0.1	0.0
PINOTAGE	-0.2	0.1	-0.1	0.0	-0.1	0.1	-0.1	-0.1	0.2	0.1	0.0	0.1
SAUVIGNON BLANC	0.0	-0.2	-0.4	**-0.5**	0.1	0.3	0.1	0.2	-0.1	0.3	0.1	0.2
GAMAY NOIR	0.4	0.3	-0.1	-0.2	0.2	0.0	-0.2	0.1	-0.3	0.0	-0.2	0.1
GEWURZTRAMINER	0.3	0.2	-0.2	0.0	0.1	-0.1	-0.1	0.2	-0.3	-0.1	-0.1	0.0
MERLOT	**0.6**	**0.5**	0.0	0.2	0.3	0.0	0.0	0.1	**-0.5**	-0.1	0.0	-0.2
MORIO MUSCAT	0.1	0.0	-0.3	-0.2	0.0	-0.1	-0.1	0.2	-0.1	-0.1	-0.1	0.2
RUBY CABERNET	0.1	0.4	0.4	**0.5**	0.3	0.0	0.0	-0.1	-0.1	-0.1	0.0	-0.2
SEMILLON	0.2	**0.5**	0.2	0.3	0.2	-0.1	-0.3	-0.1	-0.1	-0.2	-0.3	0.0
TINTA BAROCCA	0.0	0.2	-0.1	-0.2	0.0	-0.1	0.0	0.0	0.0	-0.1	0.1	0.2
WEISSER RIESLING	-0.4	-0.5	**-0.7**	**-0.5**	-0.2	0.0	-0.1	0.2	0.3	0.1	0.0	0.3
WYNDRUIF VARIA	0.3	0.2	0.1	0.2	0.2	0.3	-0.2	-0.2	-0.4	0.3	-0.2	-0.2
SPF1	0.3	0.1	-0.4	-0.2	0.2	0.1	0.0	0.2	-0.3	0.1	0.0	0.1
SPF2	**0.6**	**0.6**	0.3	0.4	0.4	0.0	-0.1	-0.1	**-0.5**	-0.1	-0.1	-0.2
SPF3	0.0	0.1	0.0	0.0	0.0	0.1	-0.1	-0.1	0.0	0.0	-0.1	0.1

Chapter 6: Results and Discussion (3) - Simulated grape yield at farm scale

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6.1. Model validation

At Langverwacht (Fig. 6.1), the model tends to overestimate the yields (except for Merlot) and has periods of good performance. The model is able to capture observed yield deficit for Ruby Cabernet (1999, 2005, 2011 and 2013), Sauvignon Blanc (2005 and 2013), Merlot (2008 and 2010) and Chardonnay (2008 and 2010). Similarly the model is able to capture the observed yield surplus for Ruby Cabernet (2002 – 2003, 2006 – 2007 and 2012), Sauvignon Blanc (2006 – 2007 and 2012), Merlot (2006 – 2007 and 2013) and Chardonnay (2012). At Vink Rivier (Fig. 6.2) the model overestimates the yields for Shiraz and underestimates the yields for Colombar. The model is able to capture observed yield deficit for both Shiraz and Colombar for some years (2010 – 2011), while capturing observed yield surplus for both cultivars during other years (2008 and 2012).

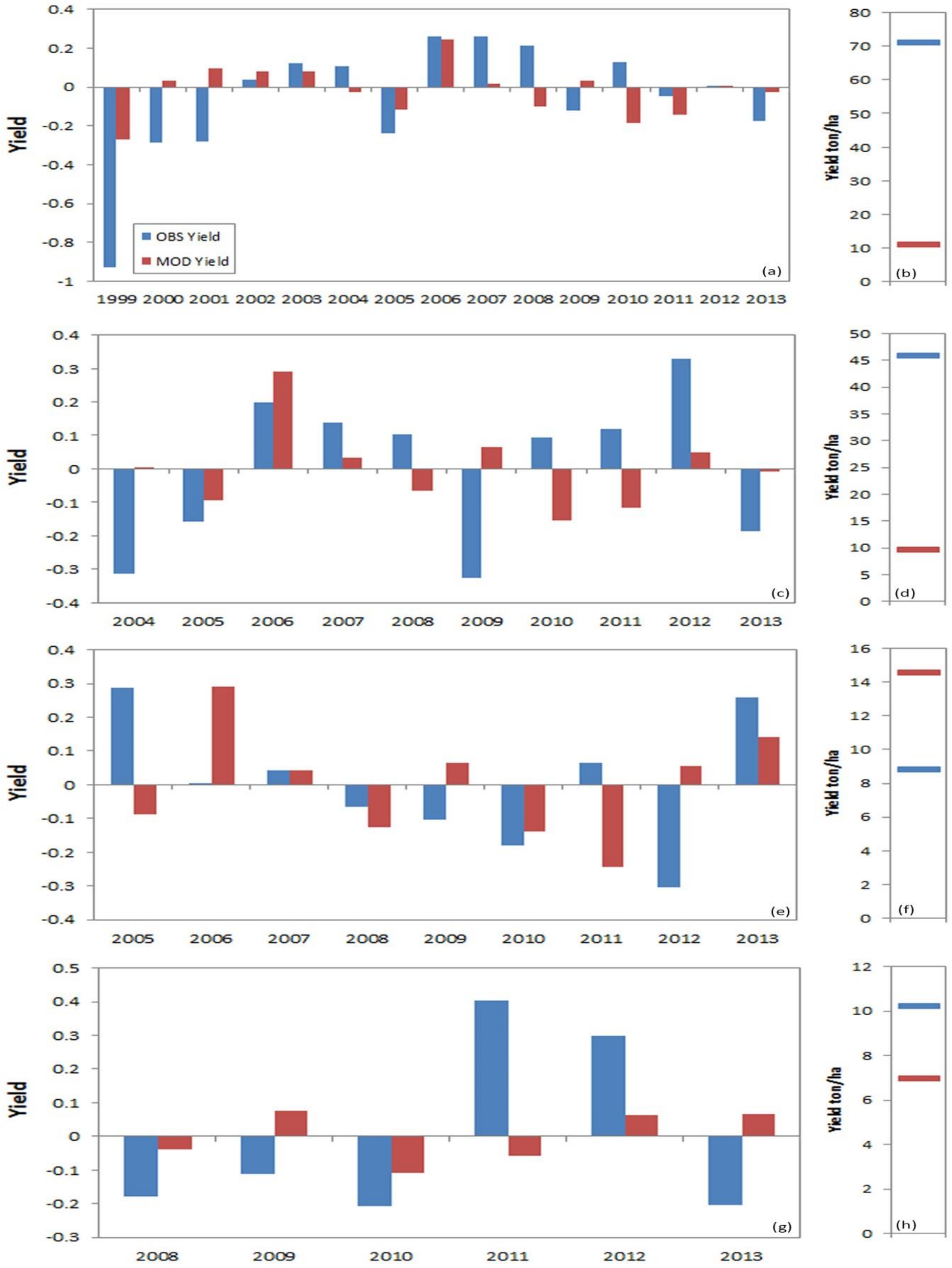

Figure 6.1. The inter-annual variation of observed (blue) and simulated (red) annual yield anomalies for cultivar at Langverwacht. Left panels show the normalised anomaly for (a) Ruby Cabernet, (c) Sauvignon Blanc, (e) Merlot, (g) Chardonnay. Right panels (b, d, f and h) show average yield (tons per hectare) used in obtaining the anomalies.

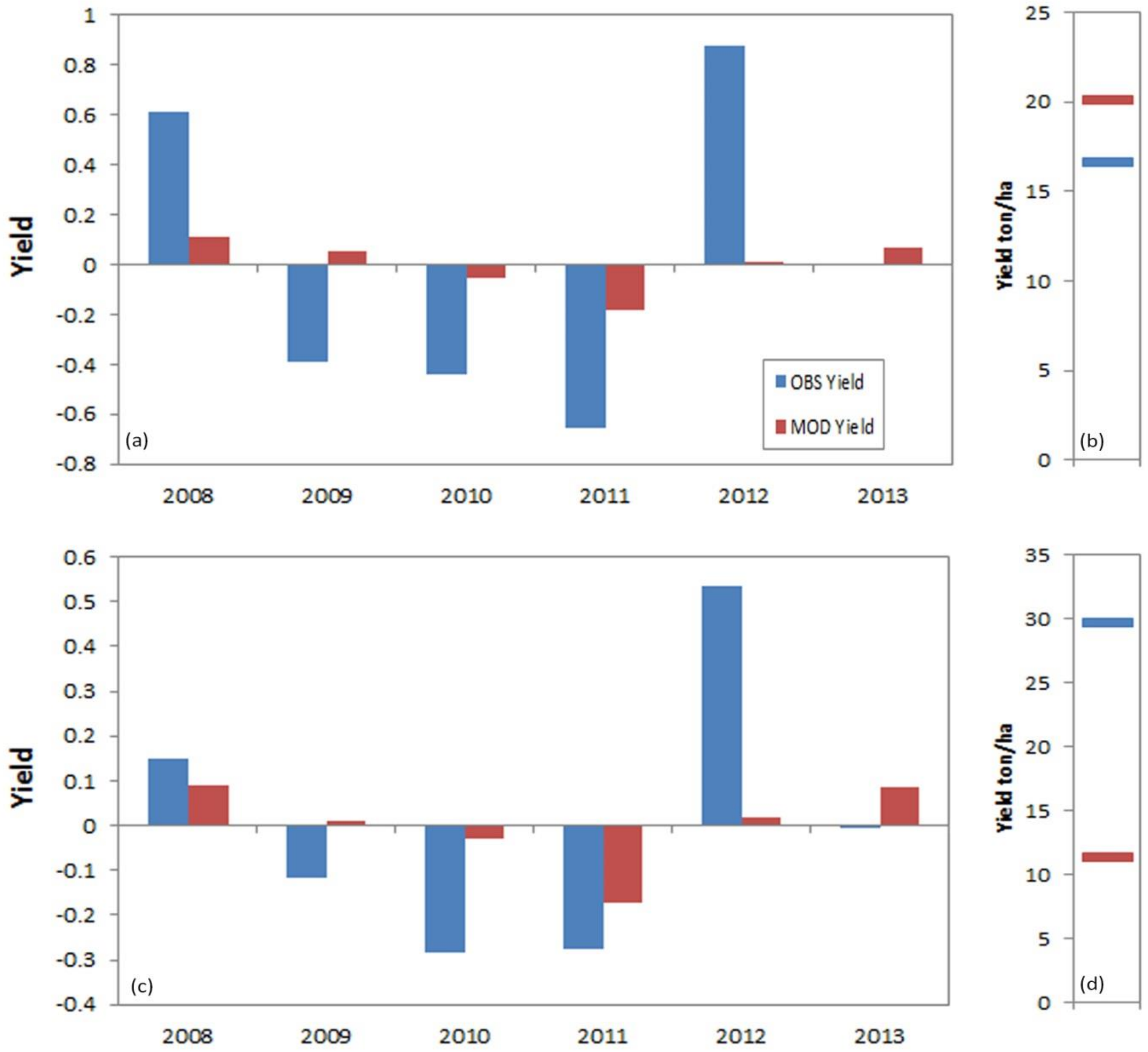

Figure 6.2. The inter-annual variation of observed (blue) and simulated (red) annual yield anomalies for cultivar at Vink Rivier. Left panels show the normalised anomaly for (a) Ruby Cabernet, (c) Sauvignon Blanc, (e) Merlot, (g) Chardonnay. Right panels (b, d, f and h) show average yield (tons per hectare) used in obtaining the anomalies.

The simulated yields show low correlations and relatively high normalised standard deviation (NSD) when compared with the observed yields (Fig 6.3). The model performs best in simulating the yield variability with Shiraz (r = 0.602) and worst with Chardonnay (r = 0.28) (Fig 6.3). Similar to the correlation, only one of the yields show low NSD. Merlot (NSD = 0.7) has the lowest, while Ruby Cabernet (NSD = 15.2) has the highest (Fig. 6.3). The accuracy of the model in replicating the exact value of the yields for each year can be assessed by the RMSE (Table 6.1). Chardonnay (4.1 ton/ha) has the lowest RMSE (indicating highest accuracy), while Ruby Cabernet (58.1 ton/ha) has the highest RMSE (indicating lowest accuracy). Good synchronisation is evident for all the cultivars as none have a synchronisation below 50 %. The best synchronisation is shared by Shiraz and Colombar (η = 67 %) whereas the worst synchronisation is for Sauvignon Blanc and Chardonnay (η = 50 %) (Table 6.2).

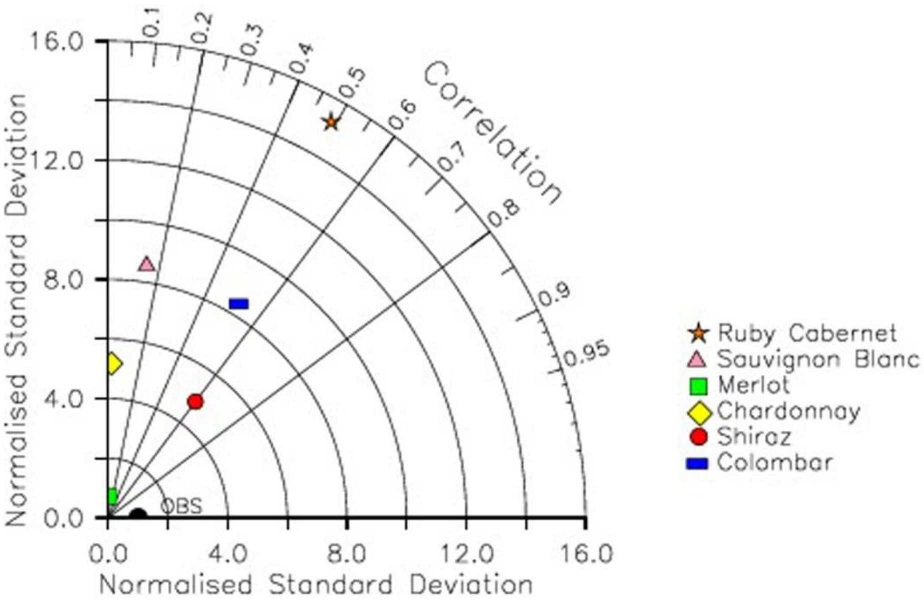

Figure 6.3. Taylor Diagram for comparing the observed (OBS) and simulated yield cultivars at Langverwacht and Vink Rivier farms.

Table 6.1. Root Mean Square Error (RMSE) for all 6 cultivars, measured in tons per hectare.

Cultivar	RMSE (Ton/ha)
Ruby Cabernet	58.1
Sauvignon Blanc	36.3
Merlot	6.3
Chardonnay	4.1
Shiraz	9.1
Colombar	19.9

Table 6.2. Model Synchronisation for each cultivar.

Cultivar	Synchronisation (%)
Ruby Cabernet	60
Sauvignon Blanc	50
Merlot	56
Chardonnay	50
Shiraz	67
Colombar	67

In considering the aforementioned validation methods, the best model representation of yield is for Shiraz, as it has the highest correlation, highest synchronisation, second lowest NSD, and third lowest RMSE. Similarly, the lowest model representation is for Sauvignon Blanc, as it has the third lowest correlation, lowest synchronisation and second highest NSD and RMSE. The accuracy of the model varies from year to year and cultivar to cultivar. Poor model performance is evident for replicating the values, signal and amplitude of the observed yields. This is shown by the general low correlations and high RMSE and NSD. The poor performance could be as a result of developing areas of the model code, as the grapevine module is still a prototype. This means that there are aspects of the module that still need testing and calibrating or changing in order to produce a more realistic simulation of growth. Some of the poor model performance can also be attributed to the quality of the data used in the simulations.

The data requirements for the APSIM model are fairly large and consist of information that is not measured or kept by the farmers; such as phenology, soils data and exact irrigation schedules. The poor quality of information supplied by the farms means that the simulated growth of the grapevine is not met under the same conditions as those for the actual vines. Similarly, the distance of the weather station from the farm will play a role in the accuracy of the simulated yields. Therefore, more accurate data will likely result in an increase in model performance.

Although the model performance generally seems poor, it does, however, do well in simulating phase changes between model and observed yield. The low synchronisation values indicate that the model does well in simulating the phase changes from year to year. As such, the model is currently limited in its application, as it does not accurately represent the yield values. Although the model performs poorly in many areas, the good synchronisation means that the results can be used for studies focussing on the impact of changes on the yields. For instance, the actual value of yield for a year may not be accurate, but the percentage change from the observed to the simulated in a climate change context will be accurate. Similarly, external forcing (such as drought) that causes yield variability, can be used by the model. Therefore, in the context of this thesis, the APSIM model is a useful tool in analysing drought sensitivity.

6.2 Sensitivity of the drought-yield relationship to irrigation

The sensitivity of yield to drought may be dependent on the application of irrigation during each season of the grapevines' growth. In order to determine if the yield - drought relationship is sensitive to irrigation, we compared the correlation between the model simulated yields (MOD) and the model simulated yields with no irrigation (MOD_{RM}). Where the MOD_{RM} correlation is higher than the MOD correlation, the yield is more sensitive to drought, when there is no irrigation management. For instance, Table 6.3 shows that Shiraz has a higher significant correlation between drought and MOD_{RM} than MOD in SON (r = 0.8 and r = 0.3, respectively), but a higher significant correlation between drought and MOD than MOD_{RM} in DJF (r = 0.8 and r = 0.6, respectively) and JJA (r = 0.8 and r = 0.1, respectively). Colombar has higher significant correlations between drought and MOD_{RM} than MOD in SON (r = 0.8 and r = 0.2, respectively), but a higher significant correlation between drought and MOD than MOD_{RM} in DJF (r = 0.8 and r = 0.5, respectively) and JJA (r = 0.8 and r = -0.1, respectively). Ruby Cabernet has higher significant correlations between drought and MOD_{RM} than MOD in DJF (r = 0.5 and r = 0.1, respectively) and SON (r = 0.7 and r = -0.3, respectively), but a higher significant correlation between drought and MOD than MOD_{RM} in MAM (r = 0.5 and r = 0.2) and JJA (r = 0.8 and r = 0.1, respectively). Sauvignon Blanc has a higher correlation between drought and MOD than MOD_{RM} in MAM (r = 0.6 and r = 0.0). Merlot has higher significant correlations between drought and MOD_{RM} than MOD in DJF (r = 0.7 and r = -0.2, respectively) and SON (r = 0.8 and r = -0.1). Chardonnay has higher significant correlations between drought and MOD_{RM} than MOD in DJF (r = 0.7 and r = 0.0, respectively) and SON (r = 0.9 and r = 0.2, respectively), but higher significant correlation between drought and MOD than MOD_{RM} in MAM (r = 0.6 and r = -0.3) and JJA (r = 0.6 and r = 0.5).

Table 6.3. Correlation between drought (SPEI) and model simulated yield (MOD) and model simulated yield with removed management practices (MOD_{RM}) for yields from both Langverwacht and Vink Rivier stations. Significant values (>0.5) are in bold.

	DJF		MAM		JJA		SON	
Cultivar	MOD	MOD_{RM}	MOD	MOD_{RM}	MOD	MOD_{RM}	MOD	MOD_{RM}
Shiraz	**0.8**	**0.6**	0.2	-0.2	**0.8**	0.1	0.3	**0.8**
Colombar	**0.8**	**0.5**	0.1	-0.3	**0.8**	-0.1	0.2	**0.8**
Ruby Cabernet	0.1	**0.5**	**0.5**	0.2	0.1	0.2	-0.3	**0.7**
Sauvignon Blanc	0.0	0.0	**0.6**	0.0	0.0	0.0	-0.2	0.0
Merlot	-0.2	**0.7**	0.4	-0.1	0.3	0.2	-0.1	**0.8**
Chardonnay	0.0	**0.7**	**0.6**	-0.3	**0.6**	**0.5**	0.2	**0.9**

The simulated yields are sensitive to drought throughout the growing seasons (as per the significant correlations), but this sensitivity is increased during certain months, if there is no influence of irrigation. For instance the yields are more sensitive to drought if there is no irrigation during SON and DJF. These seasons overlap with the grapevines' early growth to ripening and also extend into the drier part of the year. As such, it is expected that removing irrigation management would strengthen the relationship between drought and yield, as the grapevines require more soil moisture during early growth. Thus, if the rainfall is low and there is no irrigation, the farmers will have no way to mitigate the negative impacts of drought. During MAM and JJA (which overlap with the end of ripening and harvest and dormancy), the yields are less affected by removing irrigation. JJA is the middle of winter and is most often than not the period when the greatest amount of precipitation falls within the Western Cape; therefore irrigation may not be necessary during this period, as the soil moisture is high. Consequently, additional irrigation during JJA may do more damage than good, as it can cause waterlogged conditions that are harmful to the grapevines. Similarly, since irrigation may not be necessary, removing it will not make the grapevines more susceptible to the negative effects of drought. As such, irrigation management is able to mitigate the negative effects of drought during spring and summer (when high soil moisture is needed most) but not in autumn and winter.

Chapter 7: Conclusion

7.1 Contribution of this study

This study aimed to assess the impact of drought on grape yields in the Western Cape by analysing the temporal variation of drought at farm and district scales, categorising the selected wine grape cultivar yields based on their temporal variability, determining the relationship between drought and grape yields at farm and district scales and evaluates the degree to which the APSIM model simulates wine grape yield at farm scale under different irrigation conditions. The use of SPEI and APSIM were an integral part in achieving the aforementioned aim and objectives. The APSIM model is a prototype and has not been tested extensively in a South African context (for wine grapes), which allows the results of this study to identify the extent to which the model is calibrated for wine grape farming in the Western Cape. This should provide insight into areas of the model that need to be addressed for reliable calibration.

The results from the SPEI contribute to the existing body of knowledge of agricultural drought in Robertson, Olifants River and Stellenbosch. As a result of SPEI combining the effect of temperature and rainfall on drought, the identified drought further enhances drought understanding and knowledge in these areas, where mainly SPI drought would have been measured in the past.

The limited availability of drought related studies on wine grape yields in the Western Cape means that this study can contribute additional information on drought and grapevine yields that could help to improve the current knowledge base and mitigate negative impacts, both currently and for future climates. The results contribute to the knowledge required for policy makers to understand and make informative decisions which will affect the individual wine farmers and wine grape industry. Similarly the results provide a quantitative analysis of drought impacts on grape yields which can be used by the individual farmer to assess the extent to which a predicted future seasonal drought may affect their yield.

7.2 Concluding summary

Drought in the Western Cape is a present and ever-threatening issue for farmers. The many drought periods which have occurred during the past 29 years are captured by both farm (station) and district (CRU) scales. This means that the impact of drought is prevalent to both the individual grape farms as well as the Western Cape wine industry as a whole. The major drought events of the past have been associated with years of anomalously higher temperatures as well anomalously lower rainfall. This variability is likely caused by ENSO events, as some of the drought periods occur during El Niño and wet conditions during La Nina. The current high temperatures and relatively low rainfall provides a platform for drought events to have a negative impact on grape yields. The observed farm yields indicate that drought has a negative impact on yields throughout the growing season, particularly during late bloom through dormancy. Thus, at a farm scale, harsher droughts that occur in the future will cause the yields to drop further. Alternatively, this is not reflected at a district scale, as only one yield group from Stellenbosch showed any significant relationship between yield and drought (SPEI).

This potentially means that at the district scale, drought is not a major issue for wine farmers. This could be as a result of many farms being able to mitigate the negative impact of drought through various management practices. It would make sense that farms with constant access to ample water will be able to cope with any current or future drought, as long as their supply of water does not run out. Removing the influence of irrigation showed that grapevines are particularly sensitive to drought during spring and summer. Thus the application of irrigation during these seasons was able to mitigate the negative impact of drought.

Although, at the farm scale, yields are negatively influenced by drought, this result is only relevant for the individual farmer, as other farms (under different conditions) may not have the same influence. Furthermore, Government and policy-makers need to make decisions based on the provincial scale and not based on individual farms; thus, the district scale relationships provide more informed information on how the wine grape farmers in general are impacted by drought. Since the Western Cape currently has water restrictions (which are likely to get worse in the future), the distribution of water and water rights by Government may be more effective if focussed on other crops (which are worse affected by drought) than grapevines, as it appears that most farms are able to mitigate drought impacts in one way or another. However, a policy shift to a focus on individual farms rather than on the district may be needed as the impact of drought is most evident at farm scale. This should make water policies more effective as water will be allocated to farmers that actually require it.

7.3 Suggestions for further studies

It is important to explore the effectiveness of irrigation management in mitigating drought as there is a fine balance between optimal irrigation and over or under irrigating (which may reduce yields). Thus determining quantity and timing of irrigation in mitigating drought effects will be crucial to the sustainability of the wine industry in the future. Similarly it is necessary to consider the issue of how drought affects the water supply for wine grape farmers in the Western Cape, be it by river or dams. Since wine grape farmers are able to mitigate drought impacts through irrigation, if future drought affects their ability to irrigate, there is likely to be a significant reduction in the collective yields and thus the wine industry (which contributes significantly to the GDP and job markets) may start to crash.

Although the impact of drought on district yields suggest that most farmers can manage some drought event, it is important to identify how this may impact wine quality. It goes without saying that quality and yield go hand in hand as a high yield with poor quality as well as a very low yield of high quality will cause financial strain on the farmers as well as the wine industry. As such, it is important to explore the impact of drought on wine grape quality.

This study uses irrigation management to show the sensitivity of wine grape yields to drought; however this is not the only management practice that may influence the drought yield relationship. Therefore it is important to further test and develop crop simulation models such as APSIM (on South African wine grapes), which will provide the basis for many studies to be possible. Similarly, crop simulation models should be used extensively in addressing the issues of climate change on wine grape quality and yield in South Africa. This should include the impact of individual climate variables, future drought and future climate scenarios on wine grape yield and quality.

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