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ORIGINAL PAPER

Impacts of drought on grape yields in Western Cape, South Africa

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Abstract Droughts remain a threat to grape yields in South Africa. Previous studies on the impacts of climate on grape yield in the country have focussed on the impact of rainfall and temperature separately; meanwhile, grape yields are affected by drought, which is a combination of rainfall and temperature influences. The present study investigates the impacts of drought on grape yields in the Western Cape (South Africa) at district and farm scales. The study used a new drought index that is based on simple water balance (Standardized Precipitation Evapotranspiration Index; hereafter, SPEI) to identify drought events and used a correlation analysis to identify the relationship between drought and grape yields. A crop simulation model (Agricultural Production Systems sIMulator, APSIM) was applied at the farm scale to investigate the role of irrigation in mitigating the impacts of drought on grape yield. The model gives a realistic simulation of grape yields. The Western Cape has experienced a series of severe droughts in the past few decades. The severe droughts occurred when a decrease in rainfall occurred simultaneously with an increase in temperature. El Niño Southern Oscillation (ENSO) appears to be an important driver of drought severity in the Western Cape, because most of the severe droughts occurred in El Niño years. At the district scale, the correlation between drought index and grape yield is weak ($r \approx -0.5$), but at the farm scale, it is strong ($r \approx -0.9$). This suggests that many farmers are able to mitigate the impacts of drought on grape yields through irrigation management. At the farm scale, where the impact of drought on grape yields is high, poor yield years coincide with moderate or severe drought periods. The APSIM simulation, which gives a realistic simulation of grape yields at the farm scale, suggests that grape yields become more sensitive to spring and summer droughts in the absence of irrigation. Results of this study may guide decision-making on how to reduce the impacts of drought on food security in South Africa.

1 Introduction

Grapes, one of the most widely distributed fruits in the world, are usually cultivated in unique climates (like Mediterranean climate) that can provide optimal conditions for producing high-quantity and quality grape yields (Jones and Davis 2000). The location of the Western Cape in a Mediterranean climate makes it the most favourable area for grape farming in South Africa. Western Cape grape production contributes more than 50 % of the gross domestic product (GDP) generated by wine industry in South Africa and provides more than 8 % of employment in the Western Cape (SAWIS 2010). The main challenge with grape production in South Africa generally is climate variability. The climate variability has direct (temperature, precipitation, etc.) and indirect (resource management and energy efficiency) impacts on the wine industry. For instance, in 2005, drought reduced the grape yields, threatened more about 2000 permanent and seasonal jobs in the wine industry and reduced the agricultural incomes by more than 37 million rands (about 3.7 million dollars) (Johnston 2009). Droughts, which usually reduce the surety of water supply, may impose water stress on the grapevine. However, the extent to which climate variability may influence the grape yield in the Western Cape is not clear, because many grapevine farms use irrigation management. This suggests that the impact of climate variability may be weaker on farms with irrigation system than on farms without irrigation system. Nevertheless, drought may still impose water stress on the farms with irrigation systems, due to the water restriction

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policy on agricultural sectors in the Western Cape. Hence, it is essential to understand the intensity of drought that may lead to a general decrease in Western Cape grape yields.

Grapevine development is mainly driven by temperature, though other climatic variables (such as precipitation) also contribute significantly. However, there is no general consensus on how temperature influences the grape yields. Jones et al. (2005) and Lisek (2008) show that, in California and Poland, an increase in temperature enhanced the grape yields. In contrast, Ramos and Martínez-Casasnovas (2010a) and Conradie et al. (2002) show that, in a Mediterranean climate, high temperature with long dry periods decreased the grape yields. High temperature may also affect the quality of the grapes and wine. It can increase grape sugar content, which can cause lysis in microorganisms, lead to osmotic stress and affect wine quality (de Orduna 2010). Apart from increasing the potassium level and acidity of the grapes (de Orduna 2010), high temperatures have been shown to induce flavonoid, which destroys the aroma and taste of wines (de Orduna 2010). As for precipitation, many studies (Prichard and Verdegaal 2001; Malheiro et al. 2010) have shown that low soil moisture may reduce grape yields. High precipitation either throughout the growing season or between veraison and harvest can enhance many diseases like bunch rot and downy mildew, which decreases the yields (Cahill et al. 2007; Prichard and Verdegaal 2001). Nevertheless, while the individual role of temperature and precipitation on grape yields is well studied, the drought impact, which may be different from that of individual temperature or rainfall, is not yet studied. For instances, a decrease in rainfall with an increase in temperature may lead to severe drought, while a decrease in both rainfall and temperature may not necessarily lead to drought. Hence, there is a need to specifically study the role of drought on grapevine yields.

A major obstacle in studying the relationship between drought and grape yields is using an appropriate drought index to quantify drought intensity. This is because there is no universal definition (or index) for drought. The most used drought index in South Africa is the Standardized Precipitation Index (SPI), a multi-scale drought index developed by Mckee et al. (1993). The main shortcoming of SPI is that it uses only rainfall for monitoring droughts (Sivakumar et al. 2011; Vicente-Serrano et al. 2011), because it assumes that rainfall has a stronger influence on droughts than any other climate variables. Recently, Vicente-Serrano et al. (2010) proposed a new drought index, the Standardized Precipitation Evapotranspiration Index (SPEI), which incorporates potential evapotranspiration (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 timescales. As a result, SPEI can be used to detect the temporal and geographical extension of droughts, which makes it a viable tool for drought monitoring (Ujeneza and Abiodun 2014). The present study employed SPEI in studying the relationship between drought and grape yields in the Western Cape.

The aim of this study is to examine the impacts of drought on grape yields in the Western Cape at farm and district scales. The study evaluates the temporal variations of drought index and grape yields and quantifies the relationship between them using a correlation analysis. A sensitivity experiment was performed with a crop simulation to examine the influence of irrigation management on the relationship between drought index and grape yield. It is important to note that this study aims at addressing the general impact of drought on selected yields. As such, specific cultivars are only used to express the varying effects of drought and not to compare why the effects may vary between cultivars.

2 Methodology

2.1 Data and study areas

The study analysed climate data and grape yield data from two stations (Langverwacht and Vink Rivier) in Robertson District and three districts (Robertson, Olifants River and Stellenbosch; Fig. 1) in the Western Cape. The Langverwacht station (33° 56′ S, 20° 0′ E) provides climate information for the Prospect Farm and the Boesmansdrift Farm located in the vicinity of the station (less than 8 km 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. The Vink Rivier station (33° 42′ S, 19° 42′ E) shares climate information with the Orange Grove Farm located 2 km away. Hence, the Orange Grove Farm, which grows Shiraz and Colombar cultivars, is considered part of Vink Rivier in this study. The Langverwacht station is situated in the flatland area of Robertson and represents low-lying farms in the district, while the Vink Rivier station that is located in the mountainous area represents the Mountain Valley Farms in the district. Climate data from both stations provide the climatic condition in Robertson. All the three farms used in this study are located in Robertson District. Although the three farms are smaller than most farms in the Western Cape, the cultivars grown in the three farms are representative of the cultivars planted in the Western Cape. Similarly, the viticulture practices of all the three farms are representative of Western Cape wine grape farms. The data acquired for each farm were supplied from the farm managers. Management practices such as pruning time, row spacing, irrigation and fertilisation were supplied by the respective farmers. Soil-specific data were supplied by IT Measure (www.itmeasure.com), a soil Analytics Company which manages probes located at varying depths in each cultivar block. The soils, which differ for each cultivar and each farm, include shale

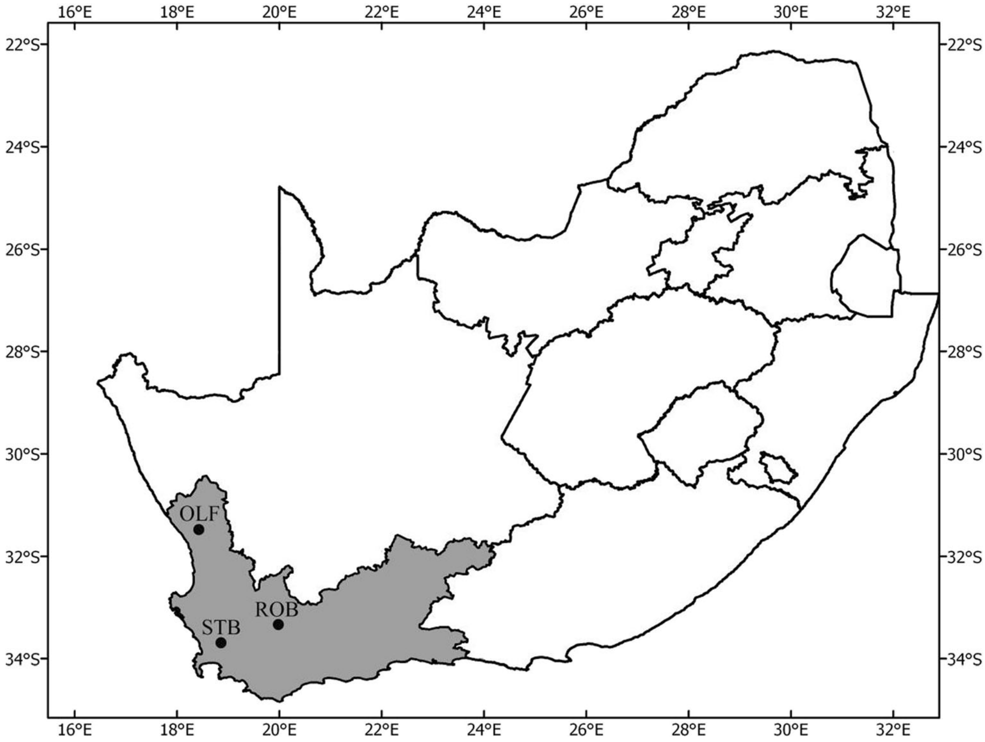


Fig. 1 Map of South Africa showing the Western Cape (in *grey*) and Robertson (*ROB*) and Olifants River (*OLF*) and Stellenbosch (*STB*) district centroids (*black dots*)

(Sauvignon Blanc), clay/sand (Ruby Cabernet), sandy loam (Chardonnay, Colombar and Shiraz) and red clay (Merlot). Although each farm fertilises and irrigates different quantities at different times, they all use similar drip-style irrigation.

Robertson District (33° 48′ S, 19° 53′ E), Olifants River District (31° 39′ S, 18° 30′ E) and Stellenbosch District (33° 55′ S, 18° 51′ E) 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). Since CRU is a gridded data set, it provides a more general climate representation than that of a single station, which may be biased by its location and topography. 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 for 26 years (1984–2009) from all the registered wine farms in the three districts. As all farms differ in some way, it is not appropriate to assume a single management practice for all. However, the common management practices in the districts include the following: pruning once a season (from the beginning of August); fertilisation twice in a season (after harvest and the beginning of August); regular irrigation (about 6 h 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.

2.1.1 Phenology

Studies have shown that the impact of climate on grapevines is crucial at the three main phenological stages: bud break, bloom and ripening up to harvest as well as during its dormancy (Ramos and Martínez-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). Following the 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 those of bud break, as warmer temperatures, high soil moisture and sufficient precipitation (or irrigation) 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). At the end of the veraison stage, all the farmers will harvest their grapes. The vines' dormancy typically occurs during winter (April–August) in which grapevine enters a dormant state. At this stage, vines' organs experience a temporary cessation of growth and metabolic processes slow down (Lavee and May 1997). Since each cultivar grows differently, the exact timing of each stage may be slightly different and, thus, the above dates are considered approximations. In reality, the phonological stages could overlap.

2.2 Calculation of drought index (SPEI)

The study used SPEI, developed by Vicente-Serrano et al. (2010), to characterise droughts at the station and district scales. SPEI uses a water balance (*D*, which is the difference between precipitation and potential evapotranspiration) to describe drought at any location. The value of SPEI typically ranges from −3 to 3 in depicting the intensity of dryness (drought; negative values) and wetness (positive values) as depicted in Table 1. This study adopted the SPEI library (Beguería and Vicente-Serrano 2013) and the R software (R Development Core Team 2012) to compute the SPEI over each station and district at 3-month scales, using the monthly rainfall and temperature data. The computation of SPEI at a 3-month scale is necessary, as this 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 [December, January and February (DJF); March, April and May (MAM); June, July and August (JJA); and September, October and November (SON)] was correlated with yield data of each cultivar. For the district level, the seasonal SPEI at each district was correlated with yield group as well as individual cultivars at the district. In the correlation, the SPEI for post-harvest seasons (JJA and SON) for a year was correlated with the grape yield of the following year. Similarly, seasonal temperature and rainfall were correlated with the 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.

2.3 Grouping of grape yields at each district

The yields of the cultivars can be grouped based on their phenology, colour (red and white), 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 capable of identifying processes that control the variability of variables in large data sets. It identifies unknown variability in the data set 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 a significant inter-annual variation in the yield data set. Hence, the results of the PCA helped reduce the dimension of the yield data from 14 (cultivars) to 3 (principal factors) in Robertson. 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.

Table 1 The seven classes of SPEI category according to value (Potop 2011)

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

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. It is therefore necessary to cluster the cultivars planted in each district, which will then cover a wide range of yields instead of just a few (Table 2). 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 fertiliser applications could produce high yield variability 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. The highly explained variance of the data (82 % at Olifants River and 61.71 % at Robertson) indicates that the factor scores accurately capture the trend of the yield anomalies and are thus a good representation for the cultivars in the respective groups.

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

The study applied the Agricultural Production Systems sIMulator (APSIM) crop model to simulate grape yields (Keating et al. 2003). The current vine module is a prototype and is a sub-module of the PLANT 2 module (Robertson et al. 2002). The grapevine crop module, VINE, describes the development, growth, yield and 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 (Probert 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

Table 2 The PCA loadings (rotated) for Robertson (RPF1–RPF3), Olifants River (OPF1 and OPF2) and Stellenbosch (SPF1–SPF3) grape yields (27 cultivars)

Cultivar	Robertson			Olifants River		Stellenbosch		
	RPF1	RPF2	RPF3	OPF1	OPF2	SPF1	SPF2	SPF3
Colombar	*0.91*	0.17	0.17	0.89	0.36	0.72	0.06	0.54
Sauvignon Blanc	*−0.5*	−0.05	−0.08	*−0.79*	*−0.53*	*0.81*	−0.38	−0.19
Pinotage	0.19	*−0.5*	*0.76*	*−0.78*	*−0.5*	−0.03	−0.05	*0.94*
Cabernet Sauvignon	−0.32	−0.44	*0.54*	0.21	*0.9*	0.01	*0.79*	−0.09
Clairette Blanch	0.2	0.08	*0.63*	*0.59*	*0.64*	*0.52*	*0.52*	0.49
Chenin Blanc	*0.6*	*0.52*	−0.06	*0.92*	0.26	–	–	–
Raisin Blanc	*−0.57*	*0.65*	0.15	0.31	*0.9*	–	–	–
Chenel	0.1	0.17	*0.86*	*0.73*	−0.12	–	–	–
Chardonnay	*0.78*	−0.31	0.19	–	–	*0.69*	0.43	−0.44
Pinot Noir	0.24	*0.7*	−0.25	–	–	*0.78*	−0.04	0.06
Semillon	–	–	–	*0.82*	0.41	−0.01	*0.63*	*0.57*
Tinta Barocca	–	–	–	0.49	*0.83*	−0.06	−0.01	*0.76*
Weldra	*0.54*	0.05	−0.23	–	–	–	–	–
Muskadel (red)	−0.02	*0.5*	−0.08	–	–	–	–	–
Ugni Blanc	0.04	*0.88*	0.14	–	–	–	–	–
Shiraz	−0.22	−0.18	*0.81*	–	–	–	–	–
Fernao Pires	–	–	–	*0.87*	0.35	–	–	–
Harslevelu	–	–	–	*0.87*	0.1	–	–	–
Bukettraube	–	–	–	0.49	*−0.69*	–	–	–
Gamay Noir	–	–	–	–	–	*0.69*	0.36	−0.41
Gewurztraminer	–	–	–	–	–	*0.9*	0.08	−0.03
Mario Muscat	–	–	–	–	–	*0.8*	−0.1	−0.35
Merlot	–	–	–	–	–	*0.52*	*0.75*	−0.32
Weisser Riesling	–	–	–	–	–	*0.52*	*−0.7*	−0.05
Ruby Cabernet	–	–	–	–	–	−0.29	*0.6*	−0.09
Wyndruif Varia	–	–	–	–	–	0.19	*0.59*	0.09
Carigan	–	–	–	–	–	−0.33	−0.06	*0.76*
Explained variance (%)	*20.87*	*20.26*	*20.58*	*50.22*	*32.47*	*30.63*	*20.81*	*20.87*

Significant loadings (>0.50) are in italicized

is determined by thermal time and is calculated from three hourly air temperatures interpolated from the daily maximum and minimum temperatures. 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 and management practices for a farm as input data to simulate the cultivar growth and yield on the farm. Temperature, rainfall and solar radiation data for Langverwacht and Vink Rivier were supplied by the ARC-ISWC and adjusted to the APSIM MET file format. This study uses soil data as supplied and calculated by IT Measure; the data were available up to a depth of 80 cm (the extent of the soil probes) at intervals of 20 cm. The aforementioned soil characteristics, supplied by IT Measure, are specific for each cultivar (collected from the onsite probes) and were used in conjunction with regular soil surveys to build up a soil database as required by APSIM. The parameters required by APSIM to simulate management, growth and soils were fitted for each cultivar at the farm scale. As such, the pruning, irrigation, fertilisation, phenology and soil characteristics were unique for each cultivar. It is important to note that some phenology information was not directly available and was thus estimated based on its relation to other management practices. For instance, budding was estimated at approximately 1 week at either side of the first fertilisation (post-dormancy).

Since APSIM does not currently have a yield function, berry live fresh weight (BerryLiveFWt) was used to approximate yield. The aforementioned data were used to initialise the model and generate the model-simulated yield (MOD). In assessing the sensitivity of the drought-yield relationship to irrigation management, the simulations were rerun with irrigation management being removed and the model-simulated yield with no irrigation ($\mathrm{MOD_{RM}}$) was generated.

The simulated yields are evaluated with reference to the observed yield at each farm. In assessing the model's ability to simulate phase changes in the yield, we used synchronisation, defined as (Misra 1991) follows:

$$\eta = \left(\frac{n - n'}{n}\right) \times 100\%$$

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. Synchronisation has been used to evaluate the accuracy of phase changes between the model and the observed data (Matthew et al. 2014; Tozuka et al. 2013).

2.5 APSIM synchronisation

The APSIM model has many uses as a complex agro-climate analysis tool; however, this study focuses on the changes in the yield from year to year and thus focuses on the phase synchronisation ability of the model. Good synchronisation is evident for all the cultivars as none of them 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 3). The greater synchronisation could be achieved through further development 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 synchronisation errors can also be attributed to the quality of the data used in the simulations. The data requirements for the APSIM model are large and consist of information that is not measured or kept by the farmers, such as phenology, soil 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. The relatively high synchronisation values indicate that the model does well in simulating the phase changes from year to year. This means that the results can be used for impact studies focussing on the changes in the yields from year to year. Therefore, in the context of this study, the APSIM model is a useful tool in analysing drought sensitivity.

Table 3 Model phase synchronisation for each cultivar at the farm scale

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

3 Results and discussion

3.1 Temporal variability of drought index at district scale

The temporal variation of SPEI at the three districts (Robertson, Olifants River and Stellenbosch) shows that the districts have experienced moderate to severe droughts in the past few years (1984–2009) (Figs. 2, 3 and 4, respectively). In Robertson (Fig. 2), there have been five major dry (SPEI≤1.5) periods (1984, 1990, 1993, 1999–2000 and 2009) and four minor dry (SPEI≤1) periods (1986, 2003, 2004–2005 and 2008) consisting of at least moderate drought. Similarly, the district has experienced intermittent wet conditions, which include four major wet (SPEI≥1.5) periods (1985, 1989–1990, 1996–1997 and 2001) and three minor wet (SPEI≥ 1.0) periods (1991–1992, 1995 and 2004). In the Olifants River (Fig. 3), 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. However, the district also experienced intermittent wet conditions with moderate wet periods during 1987, 1996 and 2001. Lastly, in Stellenbosch (Fig. 4), 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. However, the district also experienced intermittent wet conditions with moderate to severe wet periods during 1987, 1989, 1996 and 2001.

The severe droughts 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, at all three districts, the drought in the year 2000 is owing to deficit in rainfall (around 40 % in Robertson and Stellenbosch and 50 % in the Olifants River) and above normal temperature (around 1 °C in Robertson and the Olifants River and 0.8 °C in Stellenbosch). A negative rainfall anomaly with positive temperature seems to produce more severe drought than with negative temperature anomalies. For instance, in Robertson (Fig. 2), though the rainfall deficit in 1990 (about 60 %) was higher than that in 1999 (about 20 %), the drought was more severe in 1999 than in 1990, because the temperature was

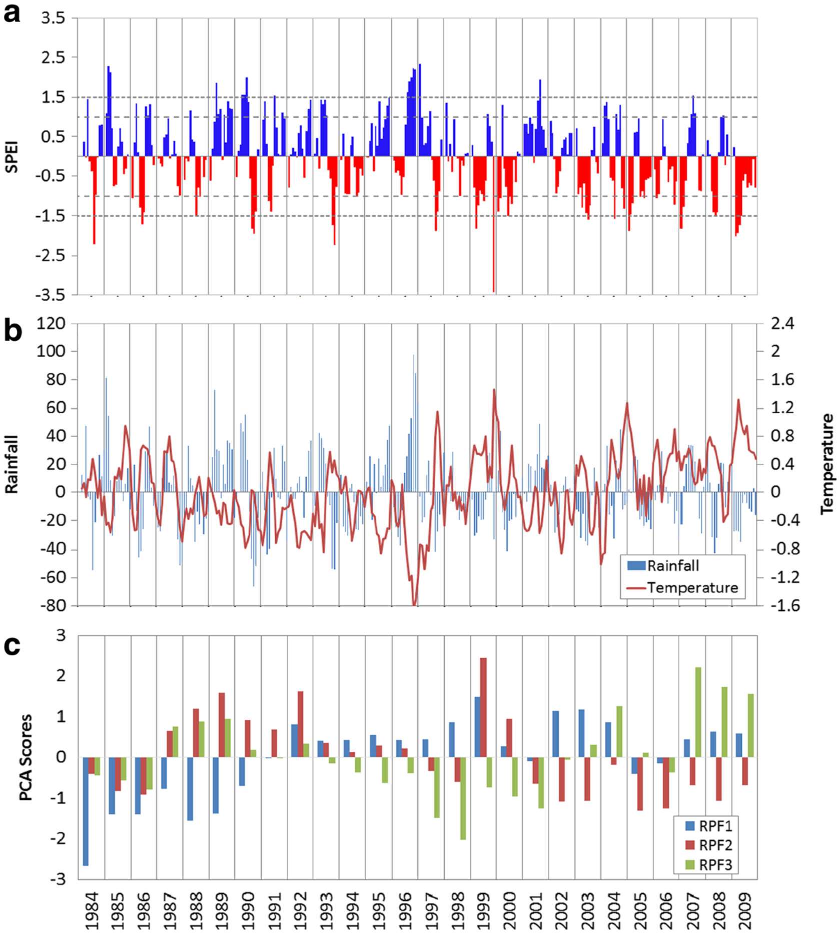


Fig. 2 The temporal variation of climate variables and yield for Robertson District (1984–2009). *a* The drought index (3-month SPEI). *b* The corresponding rainfall anomalies (normalised with the mean value; *bars*) and temperature anomalies (°C, *line*). *c* The PCA yield grouping (scores). In *a*, 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 1

higher (hence, evaporation). The drought of 1999–2000 reflected at the three districts, suggesting that severe drought events occur over the entire Western Cape.

3.2 The temporal variation of grape yields at district scale

In Robertson (Fig. 2), within a period of 26 years (1984–2009), there were three periods of significant yield deficit (1984–1986, 2001 and 2006) and one period of yield surplus (1992) where all the yields (RPF1–RPF3) had the same sign. In the Olifants River (Fig. 3), there were two periods of significant yield deficit (1985–1990 and 1992–1994) and one period of significant yield surplus (2001–2006). In Stellenbosch (Fig. 4), there were three periods of significant yield deficit (1994, 1997–1998 and 2002) and one period of significant yield surplus (2003–2009). Interestingly, some periods of yield deficit are associated with drought conditions, for example during 1984 in Robertson, 1993–1994 in the Olifants River and 1997 in Stellenbosch. There are also periods when an increase in the grape yield and droughts conceded (i.e. in Stellenbosch in 2009). This is may be due to the application of appropriate management adaptations such as additional irrigation to counter the negative effects of drought. Assessing how an annual drought affects the yield variability is a general indicator of the effects. In order to assess the actual effect of the drought, it is important to consider the impacts during the different phenology stages.

3.3 Relation between drought and yield at district scale

Table 4 shows that, at all the 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 the Olifants River show no significant correlation with temperature.

The grape yield groups show a weak correlation with rainfall in all the seasons. This is likely as a result of farmers 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

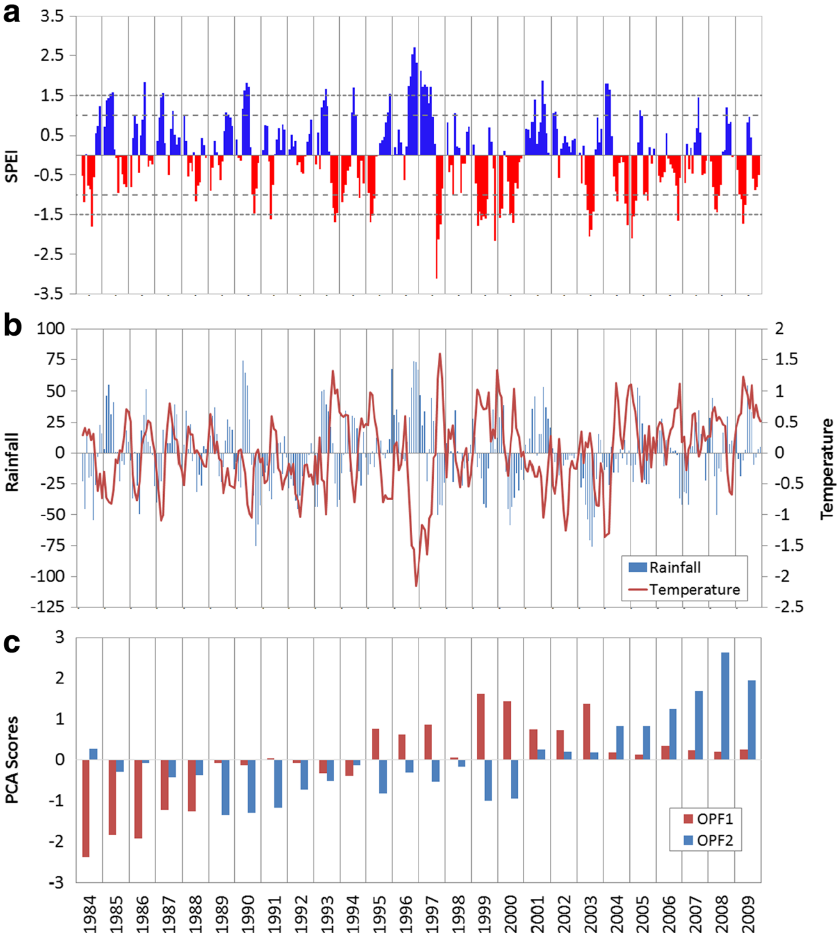


Fig. 3 Same as Fig. 2, except for Olifants River district (1984–2009)

soil moisture from deficit rainfall during budding will reduce the yield (Ramos and Martínez-Casasnovas 2010a). However, if the farmers 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 ($r=-0.5$) in DJF. The negative correlation between yield and drought index for SPF2 is associated with an increase in temperature. This could be as a result of the benefits of warm drier conditions that favour the grapes during ripening and up to harvest (Ramos and Martínez-Casasnovas 2010b). Similarly, higher temperatures during this period will dry off the grapes if there is any rainfall, as this will help to prevent diseases such as downy mildew (Cahill et al. 2007).

3.4 Temporal variability of drought index at farm scale

The temporal variation of SPEI at the two stations (Langverwacht and Vink Rivier; Figs. 2 and 3, respectively) shows that both stations have experienced moderate and severe droughts in the past few years (1999–2013 and 2008–2013, respectively). In Langverwacht (Fig. 2), 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. However, the station also experienced intermittent wet conditions with moderate to severe wet periods during 2002, 2006 and 2008. On the other hand, in 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), followed by the minor drought, which occurred from 2012 to 2013 (Fig. 3). The station also featured one severe wet period (2008–2009) and one moderate wet period (2012) (Fig. 3). Since the two stations are close to each other, it is no surprise that the severe drought of 2010 reflected in both stations.

In most cases, the drought conditions also 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 % in Langverwacht and 55 % in Vink Rivier) and warmer temperature (about 0.1 °C in Langverwacht and 0.4 °C in Vink Rivier). A negative rainfall

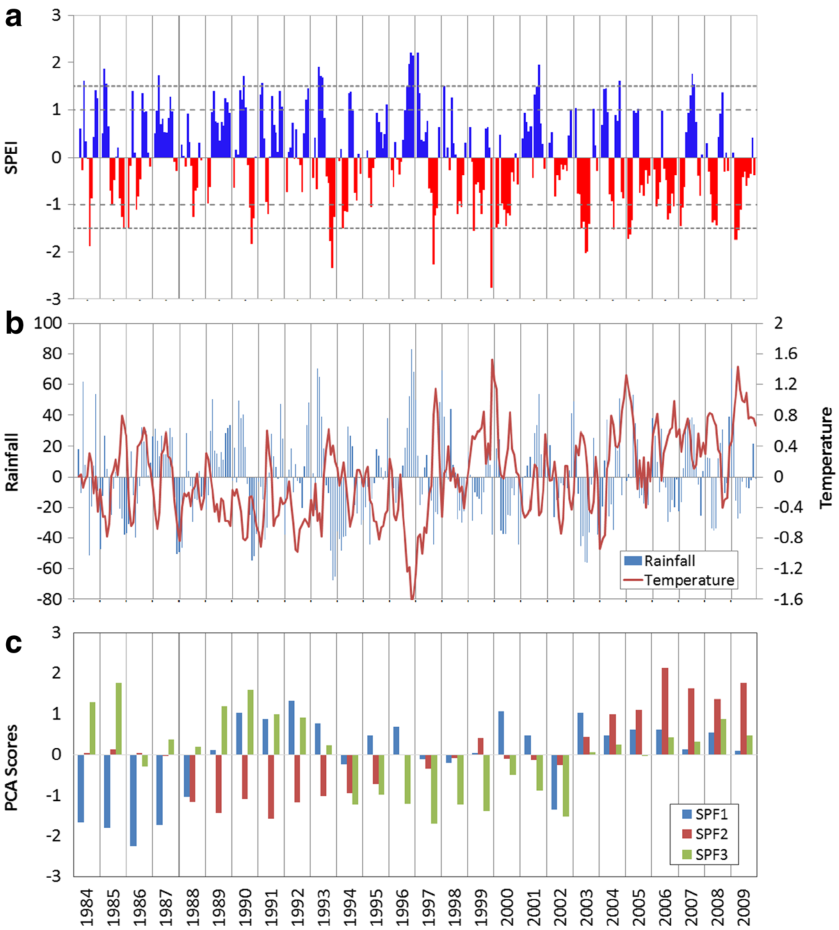


Fig. 4 Same as Fig. 2, except for Olifants River district (1984–2009)

anomaly with positive temperature seems to produce more severe drought than with negative temperature anomalies. For instance, in Langverwacht (Fig. 3), though the rainfall deficit in 2001 (about 50 %) was higher than that 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

Table 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 (RPF1–RPF3), Olifants River (OPF1 and OPF2) and Stellenbosch (SPF1–SPF3)

Cultivar	Temperature				Rainfall				Drought index (SPEI)			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
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	0.1	−0.1	0.1
RPF3	0.2	*0.6*	0.1	0.1	0.1	0	0.3	−0.1	−0.3	−0.1	0.2	−0.2
OPF1	0.3	0.2	−0.2	−0.2	0.1	−0.2	0	0	−0.4	−0.3	0	0.2
OPF2	0.1	0.4	0.2	0.2	0	0.1	0.1	−0.2	−0.1	−0.2	0	−0.3
SPF1	0.3	0.1	−0.4	−0.2	0.2	0.1	0	0.2	−0.3	0.1	0	0.1
SPF2	*0.6*	*0.6*	0.3	0.4	0.4	0	−0.1	−0.1	*−0.5*	−0.1	−0.1	−0.2
SPF3	0	0.1	0	0	0	0.1	−0.1	−0.1	0	0	−0.1	0.1

fall within the neutral phase El Niño Southern Oscillation (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, water balance deficit in the soil).

The results show the occurrence of drought over the two stations and 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 of 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.

3.5 The temporal variation of grape yields at farm scale

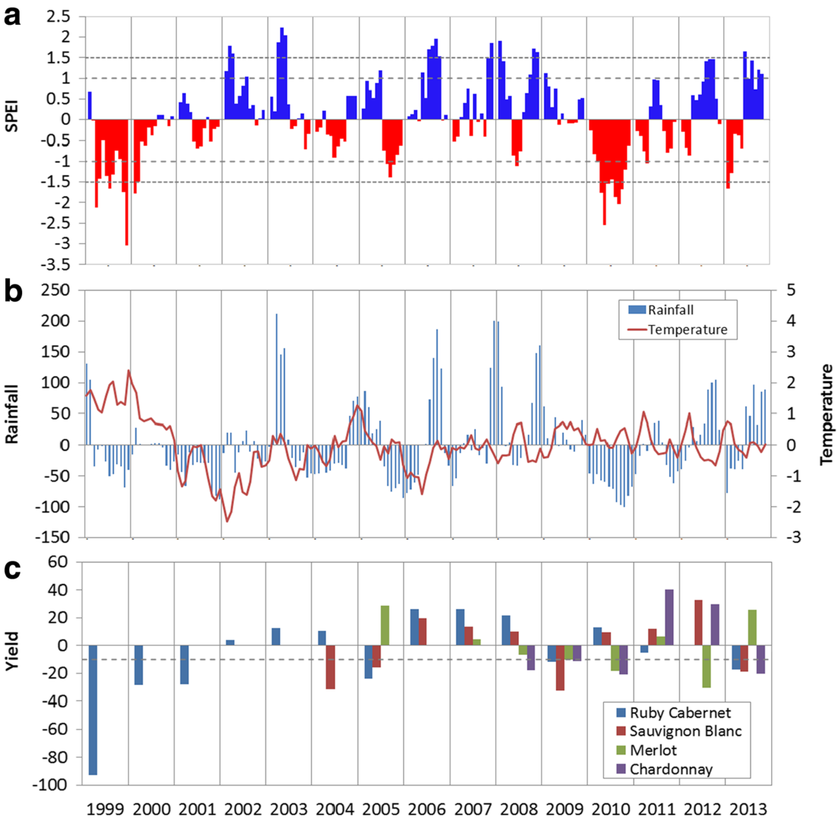
The grape yields in Langverwacht and Vink Rivier vary from year to year and from one cultivar to another. Given that a decrease of more than 10 % in grape yield may have substantial impacts on the income of a grape farmer (Cooper et al. 2012), we use 10 % as the threshold to identify significant decrease (or increase) in the yield. In 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 (2006–2007) (Fig. 5). Interestingly, the yield deficit during 1999–2000 coincides with a severe drought period. Similarly, the significant yield surplus coincides with wet conditions.

In Vink Rivier (Fig. 6), within the 6-year period (2008–2013), there is a period of significant deficit (2009–2011) and a period of significant surplus (2012). The deficit yield coincides with the severe drought in 2010, while the yield surplus coincides with the wet conditions during 2012. There are some agreements in the grape yield variability at the two stations. For instance, both stations report significant deficit in 2009. Discrepancies may be owing to the different averaging periods of the data, and it may also be owing to a difference in management and soil type. It is clear that drought influences the yield to some extent; however, periods where there is drought as well as surplus yields suggest the other factors contributing to this relationship. One such factor could be the timing of the drought, as the vines are susceptible to drought effects differently throughout different stages of the season.

3.6 Relationship between grape yields and climate variables at farm scale

Table 5 shows that at each farm, the sensitivity of the grape yields to the climate variables (temperature, rainfall and

Fig. 5 Same as Fig. 2, except for Langverwacht farm (1999–2013)



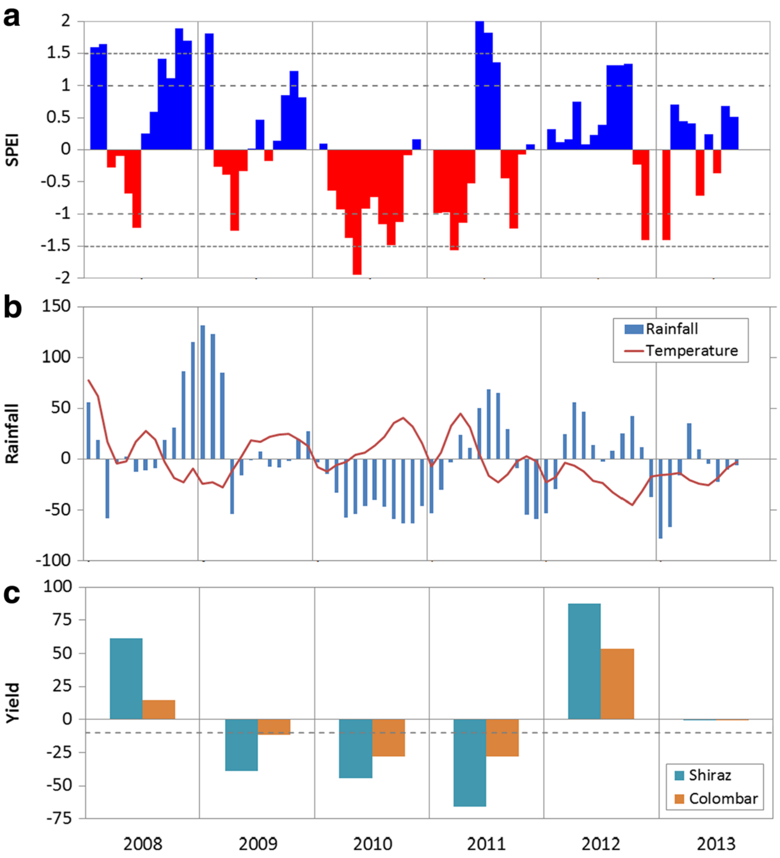


Fig. 6 Same as Fig. 2, except for the Agter-Vink River (2008–2013)

drought) varies with seasons (i.e. phenological stages). Some grape yields show a significant correlation with temperature (i.e. Colombar and Chardonnay). The general negative correlation between yield (excluding merlot) and seasonal temperature found in this study is consistent with previous studies (e.g. Ramos and Martínez-Casasnovas 2010a). The strong general negative correlation with temperature in JJA could be as a result of the grapevines' ability to accumulate the optimal number of chill units during dormancy. 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 and Whetton 2007; Lavee and May 1997). Similarly, the increase in temperature associated with drought during this stage can be as a result of the effect of cold days during winter, such that they 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

Table 5 The coefficient of correlation (r) between the observed yields and the climate variables (temperature, rainfall and drought index) for different seasons (DJF, MAM, JJA and SON)

Cultivar	Temperature				Rainfall				Drought Index (SPEI)			
	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 significant vales (r>0.5) are in italicized with studies such as Ramos and Martínez-Casasnovas (2010b) or Bruwer (2010) that show that grapevines require drier conditions at veraison. This disagreement is likely as a result of location and cultivar differences. The location of the vineyards in terms of its orientation, climate, altitude and soil type will affect how the vines are affected by temperature. Since the location and thus conditions in the study by Ramos and Martínez-Casasnovas (2010b) and Bruwer (2010) as well as the cultivars used are different to that of this study (Robertson) some discrepancies are likely to occur. 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 grape yields show significant correlation with rainfall in some seasons (i.e. Shiraz and Chardonnay during JJA). 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) (Table 5). 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. Reasons for this could be due to management or rootstock differences. However it is important to note that this study is not focussed on the differences between the cultivars, but rather what the general effects are. 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.

The strong correlation between the yield and drought index may be linked to the influence of rainfall and temperature on the yields. For example, Shiraz and Colombar show a 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 significant correlation between the yield and drought index (Merlot and Colombar during DJF). Nevertheless, a comparison of Figs. 5 and 6 shows 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 in wet conditions. For instance, the yield deficits in Langverwacht in 1999–2001 and in 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.

3.7 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 compare the correlation between the MOD and the $\mathrm{MOD_{RM}}$.

The simulated yields are sensitive to drought throughout the growing seasons (as per the significant correlations; Table 6), but this sensitivity increased during certain months,

Table 6 Correlation between drought (SPEI) and model-simulated yield (MOD) and model-simulated yield with removed management practices ($\mathrm{MOD_{RM}}$) for yields from both Langverwacht and Vink Rivier stations

Cultivar	DJF		MAM		JJA		SON	
	MOD	$\mathrm{MOD_{RM}}$	MOD	$\mathrm{MOD_{RM}}$	MOD	$\mathrm{MOD_{RM}}$	MOD	$\mathrm{MOD_{RM}}$
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*

Significant values (>0.5) are in italics if there is no influence of irrigation. 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. 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 (ripening and harvest and dormancy), the yields are less affected by removing irrigation. JJA is the middle of winter and is most often not the period when the greatest amount of precipitation falls within the Western Cape; therefore, irrigation may not be necessary as the soil moisture is high. Consequently, over-irrigation during JJA may cause more damage than good result, 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. Irrigation management is therefore able to mitigate the negative effects of drought during spring and summer (when high soil moisture is needed most) but not during autumn and winter.

4 Conclusion

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 and district scales. Major drought events have been associated with years of anomalously higher temperatures as well as anomalously lower rainfall. This variability is associated with 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 provide a platform for drought to have a negative impact on grape yields.

A comparison of the drought sensitivity at farm and district scales shows a significant decrease in the three districts. This is such that only one yield group from Stellenbosch shows any significant sensitivity to the drought index. It is likely that the majority of farms in the districts are able to mitigate the effects of drought through irrigation management. This means that as long as there is access to ample water for irrigation, the majority of farms should be able to cope with future drought. This is not true for the case study at the farm scale since it is clear that the yields are negatively impacted by drought. While comparing annual changes in yield to major drought occurrences can outline whether the impacts will be positive or negative, assessing the effects during different seasons/phenology identifies key areas where the vines are affected. The impact of drought is felt throughout the growing season, in particular during late bloom and dormancy. This coincides with early summer and winter. High temperatures and low rainfall during summer and winter can cause additional stressors on the grapevines through increased diseases, inadequate chill units, raisining and other physiological stress resulting from inadequate water uptake. 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 is able to mitigate the negative impact of drought.

The variable scales used to assess the impact of drought on grape yields (also) emphasised a dimmed effect which is visible at the district scale, in comparison to the farm scale. The spatial variability of drought occurrence, in combination with a larger range of mitigation and copping strategies available across a district, results in underestimating the yield sensitivity to drought. While over a whole district, the impacts are limited, this study shows that drought has a critical and negative impact on grape yields at the farm scale. Though the overall sector may look only partly impacted, droughts and projected increased occurrences of droughts in the future, is not favourable to the emergence of new grape farmers which would be necessary for a renewal and increase of the grape industry in the Western Cape and in South Africa.

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