Response of *Vitis vinifera* L. *cv.* Pinotage to Irrigation Strategy and Trellis System in the Breede River Valley Region: Vegetative Growth, Yield and Juice Characteristics

C.L.Howell[(1)], P.A. Myburgh[(1)]

(1) ARC Infruitec-Nietvoorbij[1], Private Bag X5026, 7599, Stellenbosch, South Africa

Accepted for publication: October 2024

Key words: bunch mass, grapevines, irrigation strategies

Pinotage is a South African bred red wine cultivar and is second only to Shiraz in terms of the country's wine exports. Since rainfall in the Breede River region is low, vineyards in this region depend on irrigation. The sensitivity of Pinotage/99R to water deficits and the most suitable irrigation strategy during water restrictions were studied in a field trial from 1998/99 until 2000/01. The possibility to produce more grapes with the same volume of irrigation water was also investigated. Irrigation strategies entailed combinations of 50% readily available water (RAW) depletion, 75% RAW depletion and no irrigation between various phenological stages, *viz.* budbreak, flowering, pea size berries, véraison, 17°B and harvest. Irrigation applied at 50% RAW depletion from budbreak in September until harvest in February was regarded as the control. Each experiment plot was split into a six-strand vertical hedge and a two-tier vertical trellis. The experiment layout was a split plot, randomised block design. Cane mass of grapevines on the two-tier trellis was lower compared to those on the six-strand hedge. Irrigation at 75% RAW depletion level until harvest tended to reduce cane mass compared to more frequent irrigation. Drier soil conditions reduced berry mass, regardless of the trellis system. Sustained water deficits reduced yield, but had little effect on juice acidity and pH. More Pinotage grapes were produced on the two-tier vertical trellis compared to the six-strand hedge with the same amount of irrigation, thereby reducing the blue water footprint and increasing the irrigation water use efficiency substantially.

INTRODUCTION

Irrigation resources are generally limited in the grape-producing regions of South Africa (Myburgh, 2018). The Breede River Valley production region, which has a Mediterranean climate, *i.e.* long, dry summers and rainfall in winter, receives on average of 116 mm of rainfall in spring and summer, followed by 164 mm in autumn and winter. Therefore, vineyards in this particular region depend totally on irrigation. Considering the possible effects of climate change on viticulture, the worst-case scenario would be that lower rainfall reduces natural water resources and higher air temperatures increase vineyard water requirements. Even if climate change does not affect vineyard evapotranspiration (ET), grape growers still need to use irrigation water more efficiently, but without compromising yield and wine quality.

Pinotage is a South African red wine grape cultivar that was bred locally in 1925 (Goussard, 2008). It yields approximately 10 to 15 t/ha of fruit. It is the most widely planted, locally bred cultivar in South Africa. The total area of vineyards planted to Pinotage comprises *ca.* 7.5% of the total area of wine grape vineyards in South Africa (SAWIS, 2023). Thirty two percent of the Pinotage vineyards are located in the Breedekloof, Robertson and Worcester areas of the Breede River Valley. In terms of wine exported from South Africa, Pinotage is only second to Shiraz. Despite the popularity of the cultivar, there is no knowledge on the sensitivity of Pinotage growth, yield and wine quality characteristics to water constraints if irrigation is, or becomes limited. Generally, vegetative growth of may impact directly and/or indirectly on grape yield and wine quality. Less irrigation reduces shoot growth tempo (Van Zyl, 1984a) as well as total shoot mass compared to more frequent irrigation (Myburgh *et al*., 1996; Conradie & Myburgh, 2000; Myburgh, 2003b; Myburgh, 2007; Bruwer, 2010; Lategan, 2011; Myburgh, 2011; Lategan & Howell, 2016;). Although vegetative growth can be manipulated by means of irrigation, yield also decreases with less irrigation (Myburgh *et al*., 1996;

[1] The Fruit, Vine and Wine Institute of the Agricultural Research Council

**Corresponding author: howellc@arc.agric.za*

Acknowledgements: The Agricultural Research Council (ARC) and Winetech for funding the project. The ARC for infrastructure and other resources. Soil and Water Science Division personnel at ARC Infruitec-Nietvoorbij for technical support, in particular Mr. Trevor Harris. Staff at ARC Robertson Research Farm.

Conradie & Myburgh, 2000; Myburgh, 2003b; Myburgh, 2007; Bruwer, 2010; Lategan, 2011; Myburgh, 2011; Lategan & Howell, 2016; Munitz *et al*., 2017; Vilanova *et al*., 2019). In drought situations, water restrictions could be imposed, thereby forcing growers to manage the limited available water to obtain maximum benefits. In order for growers to make informed decisions regarding the irrigation of their vineyards if water becomes limited, information is needed on the effect of water constraints during different phenological stages.

The water footprint (WF) of an agricultural product is the volume of water required to produce one unit of the product (Mekonnen & Hoekstra, 2010). The purpose of the WF is to create awareness of the impact that the water used for agricultural production has on the environment. The total water footprint of a crop is subdivided into three components, *i.e.* the green (WF_{green}), blue (WF_{blue}) and grey (WF_{grey}) water footprints, respectively (Mekonnen & Hoekstra, 2010). In short, the WF_{green} is the volume of rainwater involved in the crop production process. The WF_{blue} is the volume of surface and groundwater used to produce a crop. The WF_{grey} is the volume of fresh water that is required to assimilate the load of pollutants which originate from the production cycle. Globally, the total WF for grapes is estimated at 608 m^3/t of which the WF_{green}, WF_{blue} and WF_{grey} are 425 m^3/t, 97 m^3/t and 87 m^3/t, respectively (Mekonnen & Hoekstra, 2010). Given the drive towards eco-friendly grape production, as well as limited water resources, grape growers need to follow measures to ensure the lowest water footprint that is practically possible. In addition, ever increasing water tariffs and energy costs are continuously challenging growers to adopt irrigation practices that will ensure sustainable grape production. In this regard, the published water footprint values are useful as benchmarks for growers to evaluate the situation on their farms, and to reduce the water footprint of their vineyards where practically possible. In practice, however, grape growers can only manipulate the WF_{blue}. The irrigation water use efficiency (WUE_i), which is defined as the unit crop produced per unit of irrigation water, is also a measure for the efficacy of irrigation management. At the farm level, the WF_{blue} can be reduced or the WUE_i can be increased based on two approaches, *i.e.* either use less water to produce the same yield, or produce higher yields with the same volume of water.

There are various practical ways in which the WF_{blue} or WUE_i vineyards can be improved. Based purely on the application efficiency of different irrigation systems (Ley, 1994; Myburgh, 2018), converting from full surface overhead irrigation to drip irrigation could improve the WF_{blue} or WUE_i substantially. A previous study showed that the WUE_i for full surface flood irrigation could be increased from 1.9 kg/m^3 to 3.3 kg/m^3 if the grapevines are irrigated by means of narrow furrows (Myburgh, 2003a). Less frequent irrigation will reduce evaporation losses from the soil surface (Myburgh, 1998; Lategan & Howell, 2016), and thereby reduce vineyard ET (Myburgh, 2003b; Myburgh, 2007; Myburgh & Howell, 2007; Lategan & Howell, 2016). Hence, if less frequent irrigation does not decrease yield and/or wine quality substantially, it could also result in the more efficient use of irrigation water. Furthermore, it is possible to produce more grapes on bigger trellis systems (Wolf *et al*., 2003) with the same volume of irrigation water (Van Zyl & Van Huyssteen, 1980; Swanepoel *et al*., 1990). However, higher yields are mostly obtained on horizontal trellis systems. Since adequate water and deep, fertile soils are crucial for sustaining grapevines on large trellis systems, the latter might not be a viable option where water resources are limited. Another option is to increase the bearing capacity of a vineyard vertically. This can be achieved by training every second grapevine onto a higher cordon wire. Although this so-called two-tier vertical trellis system is already used by some growers, no scientific evidence on the advantages and disadvantages of the two-tier trellis could be found in literature. However, this system holds a promise to increase the effective use of irrigation water.

Considering the above-mentioned, the primary objectives of the study were to determine (i) during what stage(s) Pinotage per se is sensitive to water deficits, (ii) the most suitable irrigation strategy when water restrictions are imposed during periodic droughts and (iii) if more grapes can be produced with the same volume of irrigation water when the bearing capacity of grapevines is increased.

MATERIALS AND METHODS

Experiment vineyard

The field trial was carried out over three seasons, *i.e.* from 1998/99 until 2000/01, in a three-year-old Pinotage/99Richter vineyard on the Agricultural Research Council (ARC) Research Farm near Robertson in the Breede River Valley of South Africa. The locality has a BSk (semi-arid, cold) climate according to the Köppen-Geiger climate classification (Peel *et al*., 2007). Based on the growing degree days (GDD) of 1497°C from 1 September to 31 March (Amerine & Winkler, 1944), the specific locality is in a class II climatic region that has the potential for the production of good quality red and white table wine (Le Roux, 1974). Given the mean February temperature of 23.1°C, low acid, high pH wines can be produced (De Villiers *et al*., 1996). The sandy loam soil was representative of the Hutton and Sterkspruit forms (Soil Classification Working Group, 1991) and was deep delved to *ca.* 90 cm using a crawler tractor before planting. Grapevines were planted at a spacing of 2.75 m × 1.50 m. Irrigation was applied over the total area using 32 L/hour Eintal® micro sprinklers. Standard viticultural management practices were applied in the vineyard. The vineyard was mechanically cultivated only to establish Avena sativa L. cv. Pallinup (oats) as a winter cover crop as proposed by Fourie (2021). Full surface chemical control was applied before budbreak.

Experiment layout

To determine the effect of water deficits at various stages, different irrigation strategies were applied. These irrigation strategies consisted of eight different combinations of 50% readily available water (RAW) depletion, 75% RAW depletion and no irrigation between various phenological stages, viz. budbreak, flowering, pea size berries, véraison, 17°B and harvest as indicated in Table 1. Irrigation applied at 50% RAW depletion from budbreak in September until harvest in February was regarded as the control. For the purpose of this study, RAW was defined as the water available between -5

 DOI: https://doi.org/10.21548/45-2-6531

kPa and -100 kPa soil matric potential. It must be noted that plant available water (PAW) is the water available between -5 kPa and -1500 kPa soil matric potential. The experiment layout was a split plot, randomised block design. Each experiment plot was split into a six-strand vertical trellis and a two-tier vertical trellis to give a total of sixteen irrigation strategy/trellis system combinations, or treatments. Each of the sixteen irrigation strategy/trellis system combinations were replicated three times. Grapevines were developed onto the respective trellis systems from establishment onwards. The cordon arms of grapevines on the two-tier trellis were developed to a length of 3 m (Fig. 1). The total height of both trellis systems was 1.8 m. All grapevines were spur pruned in August, leaving two buds per spur. Plots consisted of eight experiment grapevines with two border grapevines at each end, as well as two border rows on either side of the experiment row to limit possible overlapping of treatment effects. Each experiment plot covered 247.5 m^2.

Application of irrigation strategies

Soil water matric potential was measured weekly, as well as before and after irrigations, using tensiometers at 30 cm, 60 cm and 90 cm depths. A soil water retention curve was determined for each 30 cm depth increment using undisturbed soil cores and the ceramic pressure plate technique (Klute, 1986). The water retention curves were used to determine RAW between -5 kPa and -100 kPa. The soil water retention curves were comparable for the three depth increments and total RAW amounted to 94 mm/m. Based on the soil water retention curves, 50% and 75% RAW depletion amounted to soil matric potentials of *ca.* -35 kPa and -65 kPa, respectively. Irrigation volumes were measured on S1, S3, S6 and S7 plots by means of water meters. Grapevines were not irrigated during winter months.

Vegetative growth

To quantify growth vigour, cane mass was measured at pruning in early August. The cane mass of all the experiment grapevines in each plot was determined using a hanging balance. Cane mass per plot (kg) was converted to tons per hectare. Shoots were slightly topped at the beginning of December. Topping of principal shoots was only required where irrigation was applied at 50% RAW depletion before véraison. On the two-tier trellis, shoots were topped on the

TABLE 1
Effect of different irrigation strategies (S), i.e. combinations of 50% readily available water depletion (50), 75% readily available water depletion (75) and no irrigation (NI) between various phenological stages, namely budbreak (Bb), flowering (Fl), pea size berries (Ps), véraison (Vér), 17°B and harvest (Har) on cane mass at pruning of Pinotage/99R trained onto a six-strand hedge (6-Str hedge) and a two-tier trellis near Robertson in the Breede River Valley for the 1998/99, 1999/00 and 2000/01 seasons.

Irrigation strategy						Cane mass (t/ha)					
						1989/99		1999/00		2000/01	
	Bb→	Fl →	Ps →	Vér →	17°B → Har	6-Str hedge	Two-tier	6-Str hedge	Two-tier	6-Str hedge	Two-tier
S1:	50	50	50	50	50	1.77 a[(1)]	1.43 a	2.72 a	1.69 a	1.80 ab	1.34 cde
S2:	50	NI	50	50	50	1.75 a	1.11 a	2.49 a	1.55 a	1.91 a	1.37 cde
S3:	50	NI	NI	50	50	0.70 a	0.78 a	1.98 a	1.48 a	1.91 a	1.32 cde
S4:	50	50	50	50	NI	1.33 a	1.36 a	2.10 a	1.88 a	1.71 abc	1.30 de
S5:	50	50	50	NI	NI	1.32 a	1.13 a	2.18 a	1.56 a	1.81 ab	1.28 e
S6:	75	50	50	75	75	1.16 a	1.22 a	2.41 a	1.93 a	1.87 a	1.36 cde
S7:	75	75	75	75	75	1.19 a	0.96 a	2.31 a	1.92 a	1.74 abc	1.42 cdef
S8:	75	75	75	NI	NI	0.87 a	0.68 a	1.66 a	1.24 a	1.43 bcde	1.04 e
Mean±1 std. dev.						1.26±0.38	1.08±0.26	2.23±0.33	1.66±0.25	1.75±0.18	1.30±0.12

(1) Values designated by the same letter within each season do not differ significantly ($p \leq 0.05$).

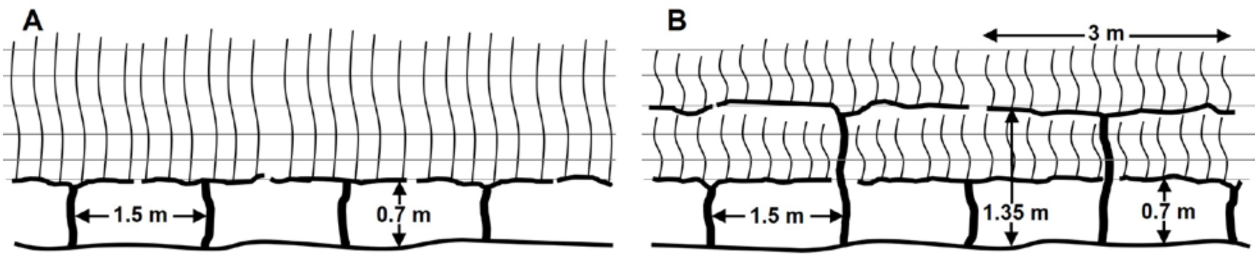

FIGURE 1
Schematic illustration of grapevines trained onto the (A) six-strand vertical trellis and (B) two-tier trellis.

lower, as well as upper cordons. In July 2001, the number of primary shoots per grapevine were counted and their length was measured using a measuring tape.

Yield components

Véraison was defined as the stage when visual observation showed that c. 95% of grape berries had changed colour. This was equivalent to stage 36 of the modified Eichhorn and Lorenz grapevine growth identification system (Coombe, 1995). At harvest, all bunches in each experiment plot were picked and counted using mechanical counters. The grapes were weighed to obtain the total mass per plot. Mean yield per grapevine was calculated and converted to tons per hectare. Bunch mass was determined by dividing the total grape mass per plot by the number of bunches per plot. The number of bunches per grapevine was calculated by dividing the total number of bunches per plot by the number of experiment grapevines per plot. Fresh berry mass was determined at harvest in all the plots. Berry samples were obtained by picking 20 berries along the longitudinal axis from each of ten bunches per experiment plot. Berries were removed from bunches by cutting through the pedicle as close as possible to the berry using a small pair of scissors (Van Schalkwyk, 2004). Berry mass was determined in the laboratory by weighing the samples using an electronic balance.

Juice characteristics

The objective was to harvest grapes when the total soluble solids (TSS) in the juice reached 24°B. The TSS, total titratable acidity (TTA) and pH in the juice were determined according to the standard procedures of Infruitec-Nietvoorbij which is the Fruit, Vine and Wine Research Institute of the Agricultural Research Council (ARC) near Stellenbosch. Total soluble solids were determined using a digital refractometer (Pocket PAL-1, Atago U.S.A. inc., Bellevue, WA, U.S.A.). Total titratable acidity and juice pH was measured using an automatic titrator (Metrohm 785 DMP Tritino, Metrohm AG, Herisau, Switzerland), against sodium hydroxide (NaOH) at a concentration of 0.33 M.

Statistical analyses

Raw data was captured and sorted in Microsoft® Excel. The data were subjected to an analysis of variance (ANOVA) by using Statgraphics®. Least significant difference (LSD) values were calculated to facilitate comparison between treatment means. Means which differed at $p \leq 0.05$ were considered significantly different.

RESULTS AND DISCUSSION

It must be noted that some of the results of S1 and S7 on the two trellis systems have been summarised previously (Myburgh, 2018 and references therein). The results obtained with all the irrigation strategy/ trellis system combinations will be discussed in detail below.

Soil water status and irrigation volumes

Grapevines were generally irrigated once a week to maintain 50% RAW depletion during summer. In order to allow 75% RAW depletion, irrigation was applied every 10 to 14 days depending on the weather (Fig. 2). On average, 619 mm of water as applied to the control strategy (S1) over the three seasons. Irrigation of grapevines at 75% RAW depletion from budbreak in September until harvest (S7), required 462 mm of water. Where water deficits were imposed from flowering to véraison (S3), an average of 572 mm of water was applied over the three years of the study. For grapevines irrigated at 75% RAW depletion with 50% RAW from flowering to véraison (S6), 509 mm of water was applied.

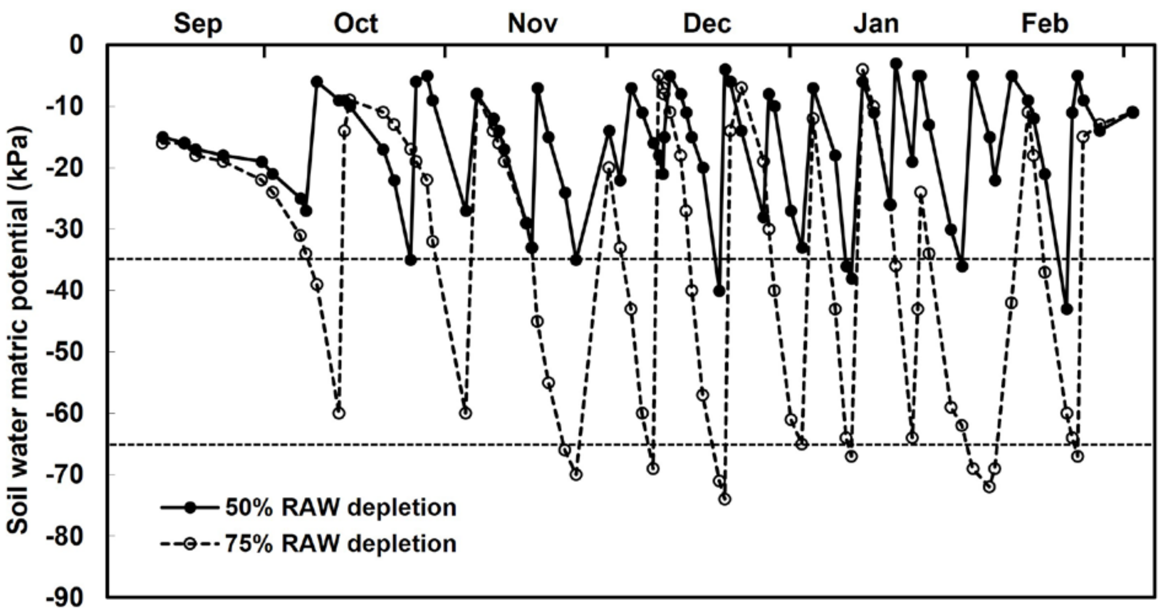

FIGURE 2
Seasonal variation in soil water matric potential (Ψm) where Pinotage grapevines were irrigated at two readily available water (RAW) depletion levels in the 2000/01 season near Robertson (redrawn from Myburgh, 2018). Horizontal dashed lines indicate the target Ψm values for 50% and 75% RAW depletion, respectively.

 DOI: https://doi.org/10.21548/45-2-6531

It must be noted that grapevines on the two trellis systems received the same volume of irrigation water.

Vegetative growth

Since some cordon arm development was still required in 1998/99, mean cane mass was lower than in 1999/00 and 2000/01 when the cordon arms were fully developed (Table 1). Although grapevines on the two-tier trellis had double the cordon length, cane mass of grapevines on the two-tier trellis generally tended to be lower compared to the six-strand hedge. Cane measurements carried out in the 2000/01 season showed that grapevines on the six-strand hedge had less primary shoots per grapevine (Fig. 3A), but longer shoots compared to the two-tier trellis (Fig. 3B). The distribution of growth potential over the longer cordons reduced the length of single primary shoots on the two-tier trellis. Based on the number of shoots per grapevine, spurs were *ca.* 14 cm apart on the six-strand hedge, whereas the spacing was *ca.* 17 cm on the two-tier trellis. However, the total cane length of grapevines on the two-tier trellis was comparable to the six-strand hedge (Fig. 4A). Visual observations revealed that the canes of grapevines on the two-tier trellis were thinner compared to the those on the six-strand hedge. In fact, cane mass per unit cane length was considerably lower for grapevines on the two-tier trellis compared to the six-strand hedge (Fig. 4B). This suggested that the tendency towards lower cane mass on the two-tier trellis was due to thinner canes compared to the six-strand hedge in the first two seasons (Table 1). In the 2000/01 season, thinner canes also contributed to the lower cane mass on the two-tier trellis compared to the six-strand hedge, except where grapevines received the least irrigation (S7 & S8).

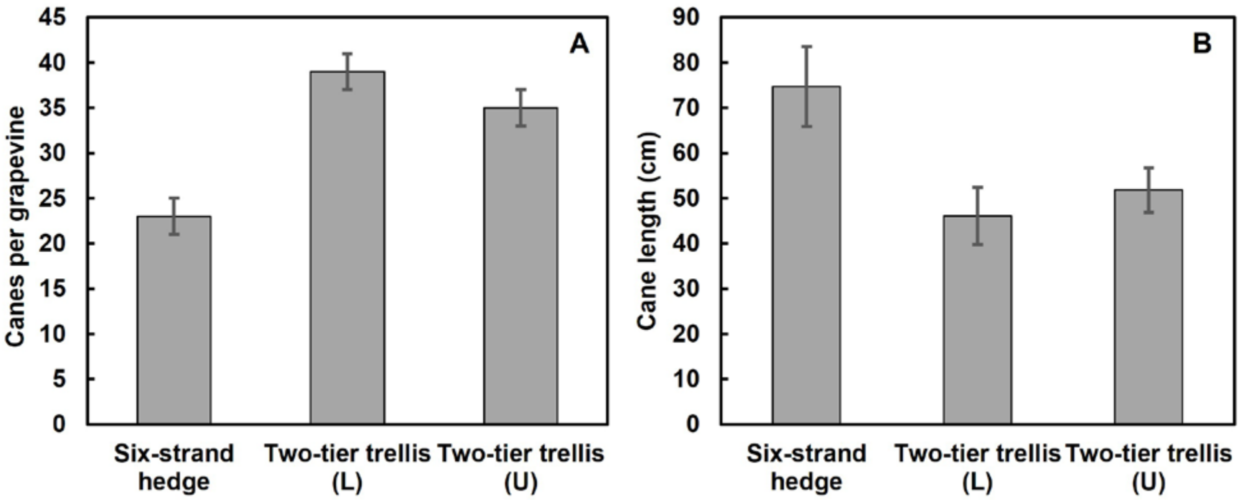

FIGURE 3

Effect of two trellis systems on (A) number of canes per grapevine and (B) cane length of Pinotage/99R in the 2000/01 season near Robertson. In the case of the two-tier trellis, L and U refer to grapevines on lower and upper cordon wires, respectively. Vertical bars indicate ±1 standard deviation.

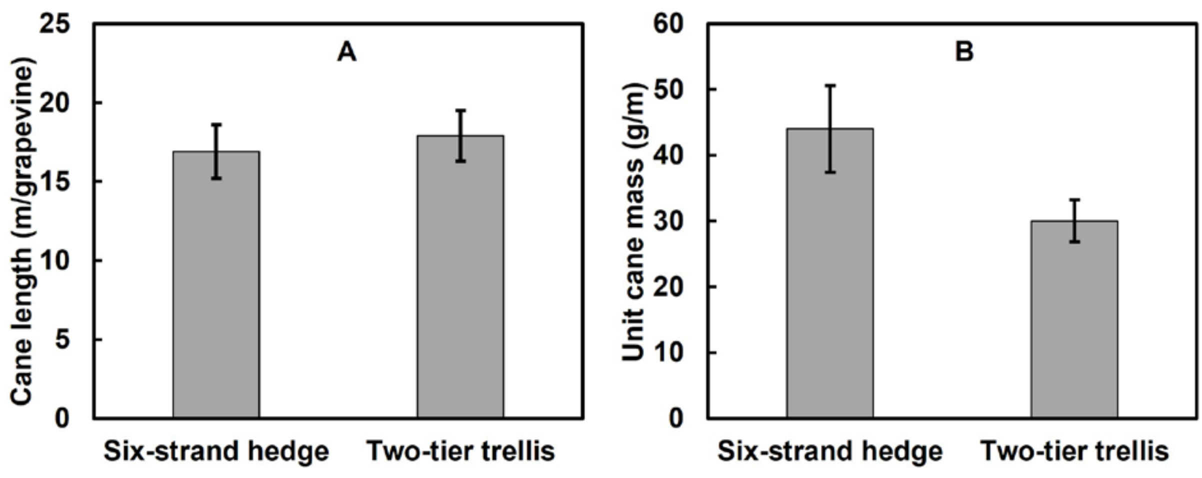

FIGURE 4

Effect of two trellis systems on (A) cane length per grapevine and (B) unit cane mass of Pinotage/99R in the 2000/01 season near Robertson. Vertical bars indicate ±1 standard deviation.

Irrigation at 75% RAW depletion from budbreak until harvest (S7) tended to reduce cane mass of grapevines on the six-strand hedge compared to irrigation applied at 50% RAW depletion over the same period (S1) in all three seasons (Table 1). In the case of the two-tier trellis, there were no consistent trends. On average, S7 tended to reduce cane mass compared to S1, irrespective of trellis system (Fig. 5). The growth reduction where irrigation was applied at higher soil water depletion levels from budbreak to harvest agrees with previous results (Van Zyl, 1984a; Myburgh, 1996; Lategan, 2011). Likewise, cane mass of suckered VSP-trained Shiraz grapevines decreased with an increase in the level of PAW depletion (Stolk, 2014; Lategan & Howell, 2016). In contrast, deficit irrigation did not reduce cane mass of Castelão grapevines, whereas no irrigation caused a substantial reduction compared to well-watered grapevines (Santos *et al*., 2005). Colombar grapevines irrigated every seven days throughout the season produced higher pruning mass in comparison to those that were irrigated every two, three or four weeks (Myburgh, 2007). Merlot grapevines subjected to continuous deficit irrigation also produced lower cane mass than those that were irrigated more frequently (Munitz *et al*., 2017).

There was generally no reduction in cane mass of grapevines on the six-strand hedge when water deficits were applied from flowering up to pea size berries (S2) compared to the control (S1) in the three seasons (Table 1). In the case of the two-tier trellis, S2 tended to reduce cane mass compared to S1 in the 1998/99 and 1999/00 seasons. Where grapevines on the six-strand hedge were subjected to water deficits over a longer period, *i.e.* from flowering to véraison (S3), cane mass tended to be lower than that of S1 grapevines in the 1998/99 and 1999/00 seasons. In the case of the two-tier trellis, S3 also tended to induce a reduction in the cane mass of grapevines compared to S1. Mean cane mass over three years followed similar trends (Fig. 5). Previous studies also showed that vegetative growth was most sensitive to soil water constraints after flowering (Van Zyl, 1984a; McCarthy, 1997).

Where irrigation at 50% RAW depletion was terminated at 17°B (S4) or véraison (S5) grapevines tended to have lower cane mass compared to S1, irrespective of trellis system for most of the seasons (Table 1). Where irrigation at 75% RAW depletion was terminated at véraison (S8), cane mass tended to be lower compared to that of grapevines that irrigated at 75% RAW depletion from budbreak until harvest for all of the seasons (S7) (Table 1). Mean cane mass over three years showed similar trends (Fig. 5). This agrees with reduced grapevine cane mass caused by post-véraison deficits compared to a fully irrigated control (McCarthy, 1997). In general, excessive shading due to vigorous vegetative growth can be detrimental to wine colour (Smart, 1982). Visual observations revealed that water deficits tended to terminate shoot elongation. Termination of shoot growth could impact positively on red grape cultivars (Williams *et al*., 1994).

Yield components

Bunch number: In the 1998/99 season, grapevines on the two-tier trellis only tended to bear more bunches compared to those on the six-strand hedge (Table 2). In contrast, grapevines on the two-tier trellis bore significantly more bunches in the 1999/00 and 2000/01 seasons when the cordon arms were fully developed. Considering the means over the three seasons, grapevines on the two-tier trellis bore significantly more bunches than the six-strand hedge (Fig. 6). Based on the shoot counts carried out in 2000/01, grapevines bore 1.8 bunches per shoot, irrespective of trellis system or irrigation strategy. This was slightly less than the target of two bunches per shoot. However, grapevines on the two-tier trellis bore only *ca.* 45% more bunches per grapevine than those on the six-strand hedge (Fig. 6). This was due to the wider spur spacing on the two-tier trellis which on average resulted in only 60% more shoots per grapevine than on the six-strand hedge (Fig. 3). Although the different irrigation strategies caused differences in bunch numbers, it was not consistent over the three seasons (Table 2). However, considering the mean values, grapevines which received

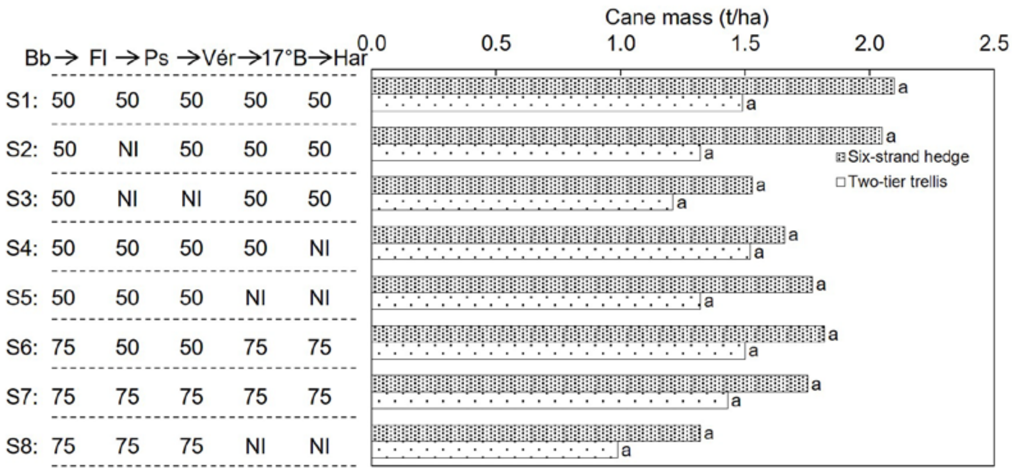

FIGURE 5
Effect of irrigation strategies (S) consisting of different levels of soil water depletion and no irrigation (NI) on cane mass of Pinotage/99R trained onto two different trellis systems near Robertson (Bb = budbreak; Fl = flowering; Ps = pea size; Vér = véraison & Har = harvest). Data are means for three years. Columns designated by the same letters do not differ ($p \leq 0.05$).

TABLE 2
Effect of different irrigation strategies (S), i.e. combinations of 50% readily available water depletion (50), 75% readily available water depletion (75) and no irrigation (NI) between various phenological stages, namely budbreak (Bb), flowering (Fl), pea size berries (Ps), véraison (Vér), 17°B and harvest (Har) on number of bunches of Pinotage/99R trained onto a six-strand hedge (6-Str hedge) and a two-tier trellis near Robertson in the Breede River Valley for the 1998/99, 1999/00 and 2000/01 seasons.

Irrigation strategy						Number of bunches					
						1989/99		1999/00		2000/01	
	Bb→	Fl →	Ps →	Vér	→ 17°B → Har	6-Str hedge	Two-tier	6-Str hedge	Two-tier	6-Str hedge	Two-tier
S1:	50	50	50	50	50	33 bcd[(1)]	45 a	21 e	33 ab	44 bc	66 a
S2:	50	NI	50	50	50	34 bc	39 ab	24 de	37 a	43 bc	63 a
S3:	50	NI	NI	50	50	26 cde	35 bc	21 e	34 ab	42 bc	61 a
S4:	50	50	50	50	NI	30 bcde	39 ab	27 cd	36 a	38 bc	68 a
S5:	50	50	50	NI	NI	31 bcde	39 ab	21 e	33 ab	38 c	69 a
S6:	75	50	50	75	75	23 e	38 ab	22 de	36 a	46 b	66 a
S7:	75	75	75	75	75	23 e	36 b	21 e	35 ab	42 bc	66 a
S8:	75	75	75	NI	NI	25 de	35 bc	23 de	31 bc	39 bc	61 a
Mean±1 std. dev.						28±4	38±3	23±2	34±2	42±3	65±3

[(1)] Values designated by the same letter within each season do not differ significantly (p ≤ 0.05).

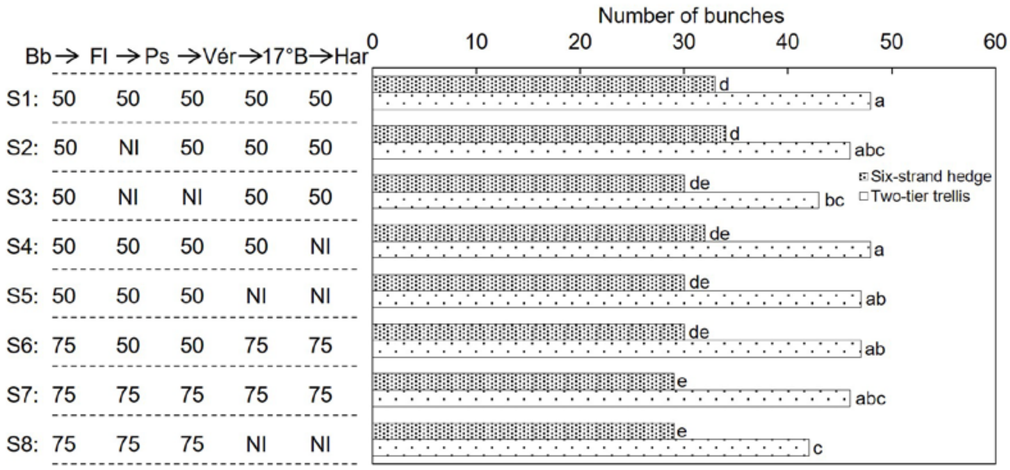

FIGURE 6
Effect of irrigation strategies (S) consisting of different levels of soil water depletion and no irrigation (NI) on number of bunches of Pinotage/99R trained onto two different trellis systems near Robertson (Bb = budbreak; Fl = flowering; Ps = pea size; Vér = véraison & Har = harvest). Data are means for three years. Columns designated by the same letters do not differ (p ≤ 0.05).

the least irrigation (S7 & S8) on the six-strand hedge had less bunches per grapevine compared to S1 and S2 which received the most irrigation (Fig. 6). Likewise, severe water constraints tended to reduce number of bunches compared to well-watered grapevines (Hardie & Considine, 1976; Santos *et al*., 2005). In the case of the two-tier trellis, irrigation at 75% RAW depletion which was stopped at véraison (S8) caused lower bunch numbers than some of the wetter treatments.

Berry mass: In general, trellis system did not seem to have any effect on berry mass in any of the seasons (Table 3). This trend also reflected in the mean values over the three seasons (Fig. 7). Water deficits from flowering to pea size berries (S2) only tended to reduce berry size compared to continued irrigation at 50% RAW depletion (S1), regardless of the trellis system (Table 3). In contrast, water deficits from flowering until véraison (S3) caused a more pronounced reduction in berry size in the 1999/00 and 2000/01 seasons. Similarly, irrigation applied at 75% RAW depletion and stopped at véraison (S8) also reduced berry size compared to S1 in the 1999/00 and 2000/01 seasons. Previous studies also showed that continued water deficits from budbreak until harvest reduced berry size (Santos *et al*., 2005; Myburgh, 2011; P´erez-Alvarez *et al*., 2021). On average, water

TABLE 3
Effect of different irrigation strategies (S), i.e. combinations of 50% readily available water depletion (50), 75% readily available water depletion (75) and no irrigation (NI) between various phenological stages, namely budbreak (Bb), flowering (Fl), pea size berries (Ps), véraison (Vér), 17°B and harvest (Har) on berry mass of Pinotage/99R trained onto a six-strand hedge (6-Str hedge) and a two-tier trellis near Robertson in the Breede River Valley for the 1998/99, 1999/00 and 2000/01 seasons.

Irrigation strategy						Berry mass (g)					
						1989/99		1999/00		2000/01	
	Bb→	Fl →	Ps →	Vér	→ 17°B → Har	6-Str hedge	Two-tier	6-Str hedge	Two-tier	6-Str hedge	Two-tier
S1:	50	50	50	50	50	1.57 a[(1)]	1.59 a	1.60 ab	1.56 abc	1.49 a	1.46 a
S2:	50	NI	50	50	50	1.60 a	1.53 a	1.51 bcde	1.46 cde	1.47 a	1.44 ab
S3:	50	NI	NI	50	50	1.51 a	1.45 a	1.46 cde	1.51 bcde	1.28 def	1.34 bcde
S4:	50	50	50	50	NI	1.58 a	1.53 a	1.64 a	1.62 ab	1.41 abc	1.43 ab
S5:	50	50	50	NI	NI	1.47 a	1.47 a	1.51 bcde	1.56 abc	1.38 abcd	1.29 cdef
S6:	75	50	50	75	75	1.63 a	1.49 a	1.61 ab	1.56 abc	1.33 bcde	1.37 abcd
S7:	75	75	75	75	75	1.43 a	1.46 a	1.55 abcd	1.43 e	1.20 f	1.40 abcd
S8:	75	75	75	NI	NI	1.46 a	1.41 a	1.48 cde	1.44 de	1.25 ef	1.30 cdef
Mean±1 std. dev.						1.53±0.07	1.49±0.06	1.55±0.07	1.52±0.07	1.35±0.10	1.38±0.06

(1) Values designated by the same letter within each season do not differ significantly ($p \leq 0.05$).

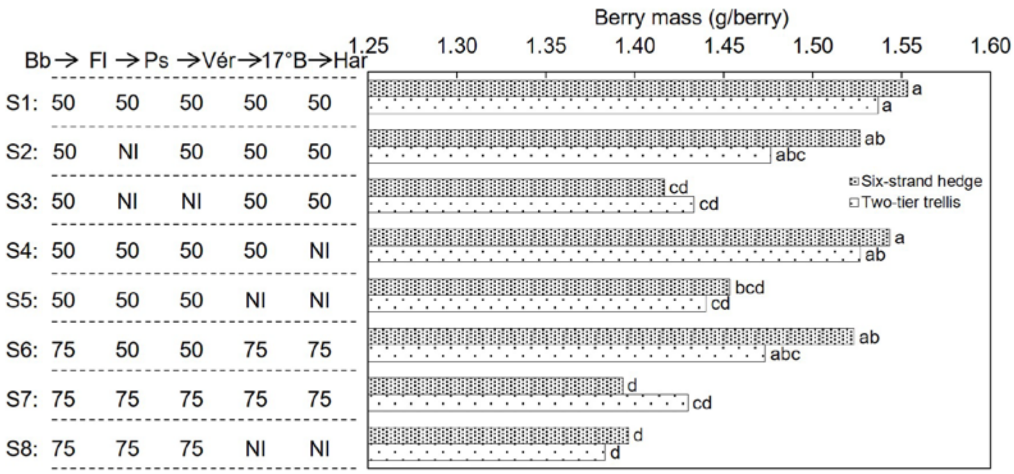

FIGURE 7
Effect of irrigation strategies (S) consisting of different levels of soil water depletion and no irrigation (NI) on berry mass of Pinotage/99R trained onto two different trellis systems near Robertson (Bb = budbreak; Fl = flowering; Ps = pea size; Vér = véraison & Har = harvest). Data are means for three years. Columns designated by the same letters do not differ ($p \leq 0.05$).

deficits from flowering to véraison (S3) significantly reduced berry mass compared to S1 on both trellis systems (Fig. 7). The reduced berry size caused by pre-véraison water deficits agrees with earlier findings (Hardie & Considine, 1976; Van Zyl, 1984b; McCarthy, 1997). Irrigation applied at 75% RAW depletion until harvest (S7) also reduced berry mass compared to S1 (Fig. 7). Similarly, irrigation applied at 75% PAW depletion from budbreak until harvest reduced berry mass compared to irrigation at 10%, 30% and 50% depletion (Van Zyl, 1984b). Irrigation applied at 50% RAW depletion and stopped at véraison (S5), as well as 75% depletion stopped at véraison (S8) also reduced berry mass (Fig. 7). Post-véraison water deficits caused a similar reduction in berry size of Cabernet Franc (Hardie & Considine, 1976).

Bunch mass: The trellis system had no effect on bunch mass in the 1998/99 and 1999/00 seasons (Table 4). In the 2000/01 season, bunches were smaller on the two-tier trellis than on the six-strand hedge for some irrigation strategies. Considering the mean bunch mass over the three seasons, the trellis system did not have any effect on bunch mass (Fig. 8). Although there were differences in bunch mass between the irrigation strategies in the 1998/99 and 2000/01 seasons, there were no consistent trends (Table 4). On average, grapevines on the six-strand trellis only produced smaller bunches where irrigation at 75% depletion was stopped at véraison (S8) compared to S1 (Fig. 8). In the

 DOI: https://doi.org/10.21548/45-2-6531

case of the two-tier trellis, pre-véraison deficits (S2 & S3) as well as deficits during berry ripening (S5) reduced bunch mass compared to S1. The sensitivity of bunch mass to pre-véraison water constraints was also found in a previous study (McCarthy, 1997). The driest irrigation strategy, *i.e.* where irrigation at 75% depletion was stopped at véraison (S8), also produced smaller bunches on the two-tier trellis compared to S1 (Fig. 8). This trend agrees with previous findings (Hardie & Considine; McCarthy, 1997; Santos *et al*., 2005). Surprisingly, irrigation at 75% RAW depletion from budbreak until harvest (S7) only tended to produce smaller bunches compared to S1 (Fig. 8). In contrast, grapevines that were subjected to water deficits from budbreak until harvest produced smaller bunches compared to more frequent irrigation (Santos *et al*., 2005; Lategan, 2011; Myburgh, 2011; Lategan & Howell, 2016).

Yield: In the 1998/99 and 1999/00 seasons, yields were generally lower compared to 2000/01 (Table 5). The lower yield in 1998/99 was due to the fact that some cordon arm development was still required. Although cordon arms were fully developed in 1999/00, mean yield was appreciably lower than in 2000/01. During 1999 and 2000, a period of drought occurred over the entire Western Cape (Araujo *et al*., 2014). This probably contributed to the low grapevine yield in the 1999/00 season. Since grapevines received adequate water via irrigation in summer, mild winter conditions such

TABLE 4
Effect of different irrigation strategies (S), i.e. combinations of 50% readily available water depletion (50), 75% readily available water depletion (75) and no irrigation (NI) between various phenological stages, namely budbreak (Bb), flowering (Fl), pea size berries (Ps), véraison (Vér), 17°B and harvest (Har) on bunch mass of Pinotage/99R trained onto a six-strand hedge (6-Str hedge) and a two-tier trellis near Robertson in the Breede River Valley for the 1998/99, 1999/00 and 2000/01 seasons.

Irrigation strategy						Bunch mass (g)					
						1989/99		1999/00		2000/01	
	Bb→	Fl →	Ps →	Vér →	17°B → Har	6-Str hedge	Two-tier	6-Str hedge	Two-tier	6-Str hedge	Two-tier
S1:	50	50	50	50	50	170 abcd[(1)]	166 bcd	218 a	228 a	219 a	199 abcd
S2:	50	NI	50	50	50	184 ab	164 bcde	195 a	194 a	206 abc	180 bcde
S3:	50	NI	NI	50	50	157 cdef	151 def	193 a	199 a	204 abc	167 f
S4:	50	50	50	50	NI	174 abc	170 abcd	214 a	214 a	210 ab	181 def
S5:	50	50	50	NI	NI	163 cdef	155 cdef	223 a	218 a	204 abc	167 f
S6:	75	50	50	75	75	172 abc	189 a	223 a	205 a	198 abcd	176 ef
S7:	75	75	75	75	75	166 bcd	154 cdef	224 a	208 a	188 cde	182 def
S8:	75	75	75	NI	NI	143 f	143 ef	200 a	189 a	186 cdef	167 f
Mean±1 std. dev.						166±12	162±14	211±13	207±13	202±11	177±11

[(1)] Values designated by the same letter within each season do not differ significantly (p ≤ 0.05).

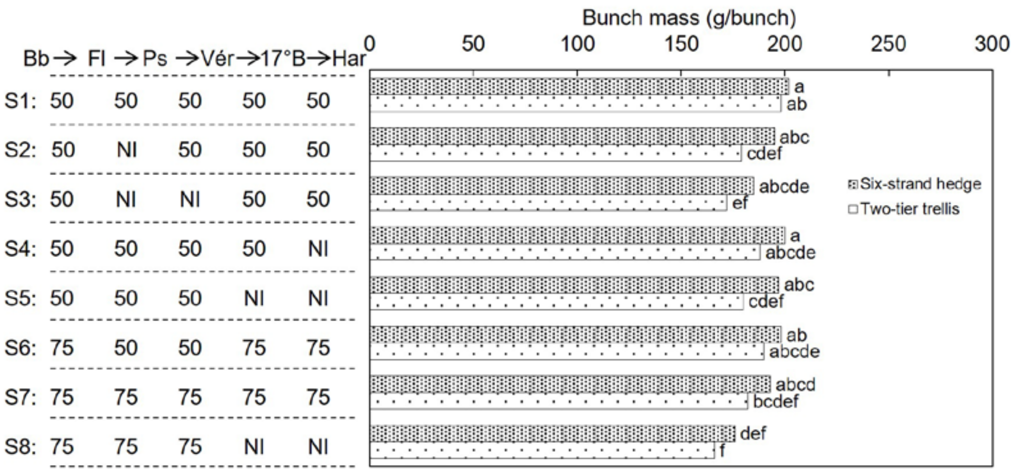

FIGURE 8
Effect of irrigation strategies (S) consisting of different levels of soil water depletion and no irrigation (NI) on bunch mass of Pinotage/99R trained onto two different trellis systems near Robertson (Bb = budbreak; Fl = flowering; Ps = pea size; Vér = véraison & Har = harvest). Data are means for three years. Columns designated by the same letters do not differ (p ≤ 0.05).

as higher air temperatures and lower humidity could have affected grapevine yield in the 1999/00 season. In fact, it was previously shown that low relative humidity and dry soil conditions in winter can reduce grapevine yields substantially (Myburgh, 2003a; Myburgh, 2003c; Myburgh & Van der Walt, 2005; Myburgh, 2008).

In the 1989/99 season, yield on the two-tier trellis was higher compared to the six-strand hedge where irrigation was applied at 50% PAW depletion from budbreak to véraison (S1) (Table 5). Where less irrigation was applied, *i.e.* S2 to S5, yield only tended to be higher on the two-tier trellis. In contrast, yield was significantly higher on the two-tier trellis where irrigation was applied at 75% RAW depletion, *i.e.* S6, S7 and S8. In the other seasons, yield was consistently higher on the two-tier trellis than on the six-strand hedge, irrespective of irrigation strategy. Although irrigation strategy had an effect on yield, it was not consistent over the three seasons (Table 5). However, on average, Pinotage grapevines irrigated at 75% RAW depletion throughout the season (S7) produced less grapes than those irrigated at 50% depletion throughout the season (S1), irrespective of trellis system (Fig. 9). Likewise, higher levels of soil water depletion maintained from budbreak to harvest reduced yield of Manto Negro and Tempranillo (Medrano *et al*., 2003), Castelão (Santos *et al*., 2005), Merlot (Myburgh, 2011), Shiraz (Lategan, 2011; Lategan & Howell, 2016), Cabernet Sauvignon (Williams & Heymann, 2017), Verdejo (Vilanova *et al*., 2019) and Bobal (P´erez-Alvarez *et al*., 2021). In contrast, Merlot grapevines only tended to produce lower yields when subjected to a higher level of soil depletion from budbreak to harvest (Munitz *et al*., 2017). On average, irrigation at 50% RAW depletion from budbreak to harvest (S1), as well as where irrigation at 75% depletion was changed to 50% depletion from flowering to véraison (S6), grapevines produced the highest yields on the two-tier trellis (Fig. 9). The lowest yields on the two-tier trellis were produced where irrigation at 50% RAW depletion was stopped from flowering to véraison (S3) and where irrigation at 75% depletion was stopped at véraison (S8). The sensitivity of grape yield towards pre-véraison, as well as post-véraison water deficits agrees with previous findings (Hardie & Considine, 1976; McCarthy, 1997). In the case of the six-strand hedge, the highest yields were produced by irrigation at 50% from budbreak to harvest (S1), as well as where irrigation at 50% was stopped between flowering and pea size berries (S2) (Fig. 9). The lowest yields on the six-strand hedge were obtained where irrigation at 50% RAW depletion was stopped from flowering to véraison (S3), as well as where irrigation was applied at 75% RAW depletion until harvest (S7) or terminated at véraison (S8). It is noteworthy that the average yield obtained on the six-strand hedge with the least irrigation, *i.e.* S8 (Fig. 9), was within the norms for Pinotage as proposed by Goussard (2008).

Juice characteristics

TSS: Given that grapes from the respective irrigation strategies were harvested as close as possible to 24°B, there were no meaningful differences in TSS of the different treatments. The sugar content at harvest varied between 23.5°B and 24.2°B (data not shown). However, it should be noted that the increase in sugar content of the grapes on the two-tier trellis was slower than that on the six-strand hedge. Depending on the season, grapes on the two-tier trellis were harvested one to two weeks after those on the six-strand hedge. This agrees with slower sugar accumulation as yield increases (Williams & Heymann, 2017; Myburgh & Howell, 2023).

TTA: In the 1998/99 season, trellis system had no effect on juice TTA, except for the higher level in grapes produced on the six-strand hedge where 75% RAW depletion was

TABLE 5
Effect of different irrigation strategies (S), i.e. combinations of 50% readily available water depletion (50), 75% readily available water depletion (75) and no irrigation (NI) between various phenological stages, namely budbreak (Bb), flowering (Fl), pea size berries (Ps), véraison (Vér), 17°B and harvest (Har) on yield of Pinotage/99R trained onto a six-strand hedge (6-Str hedge) and a two-tier trellis near Robertson in the Breede River Valley for the 1998/99, 1999/00 and 2000/01 seasons.

Irrigation strategy							Yield (t/ha)					
							1989/99		1999/00		2000/01	
	Bb→	Fl →	Ps →	Vér →	17°B →	Har	6-Str hedge	Two-tier	6-Str hedge	Two-tier	6-Str hedge	Two-tier
S1:	50	50	50	50	50		13.6 cd[1]	18.3 a	11.3 e	18.3 ab	23.5 de	31.6 a
S2:	50	NI	50	50	50		14.8 bcd	15.3 abcd	11.1 e	17.4 ab	21.4 efg	27.3 bc
S3:	50	NI	NI	50	50		9.9 efg	12.7 cde	9.9 e	16.4 bc	20.7 efg	24.8 cd
S4:	50	50	50	50	NI		12.7 cde	15.7 abc	14.0 d	18.7 a	19.4 fgh	30.0 ab
S5:	50	50	50	NI	NI		12.2 def	14.6 bcd	11.2 e	17.5 ab	18.7 gh	27.9 bc
S6:	75	50	50	75	75		9.3 fg	17.4 ab	12.0 de	17.9 ab	22.1 def	28.1 b
S7:	75	75	75	75	75		9.2 fg	13.2 cde	11.2 e	17.6 ab	19.3 fgh	29.2 ab
S8:	75	75	75	NI	NI		8.4 g	12.1 def	10.9 e	14.1 cd	17.4 h	24.7 cd
Mean±1 std. dev.							11.3±2.4	14.9±2.2	11.5±1.2	17.2±1.4	20.3±2.0	28.0±2.4

(1) Values designated by the same letter within each season do not differ significantly ($p \leq 0.05$).

 DOI: https://doi.org/10.21548/45-2-6531

changed to 50% depletion between flowering and pea size berries (S6) (Table 6). In the 1999/00 season, S6 grapes on the six-strand hedge again had higher levels of TTA than those on the two-tier trellis. However, five more irrigation strategies, *i.e.* S1, S3, S5, S7 and S8 produced more TTA on the six-strand hedge than on the two-tier trellis. In the 2000/01 season, *i.e.* the first full-bearing season, grapevines on the six-strand hedge produced higher levels of juice TTA than those on the two-tier trellis, irrespective of irrigation strategy (Table 6). This trend was probably caused by slightly cooler grapes due to less exposure to solar radiation on the six-strand hedge than those on the two-tier trellis (Kliewer 1971; Iland, 1989). However, more exposed leaves on the six-strand trellis could also have contributed towards higher juice TTA (Iland, 1989). Irrigation at 50% RAW depletion from budbreak until harvest (S1) had no effect on juice TTA compared to irrigation at 75% depletion (S7), irrespective of trellis system (Table 6). This insensitivity of titratable acidity to water constraints agrees with previous findings (Medrano *et al*., 2003; Acevedo-Opazo *et al*., 2010; P´erez-Alvarez *et al*., 2021). Although there were some differences between irrigation strategies within a trellis system, they were not consistent in any of the three seasons. On average, irrigation at 50% PAW depletion before véraison followed

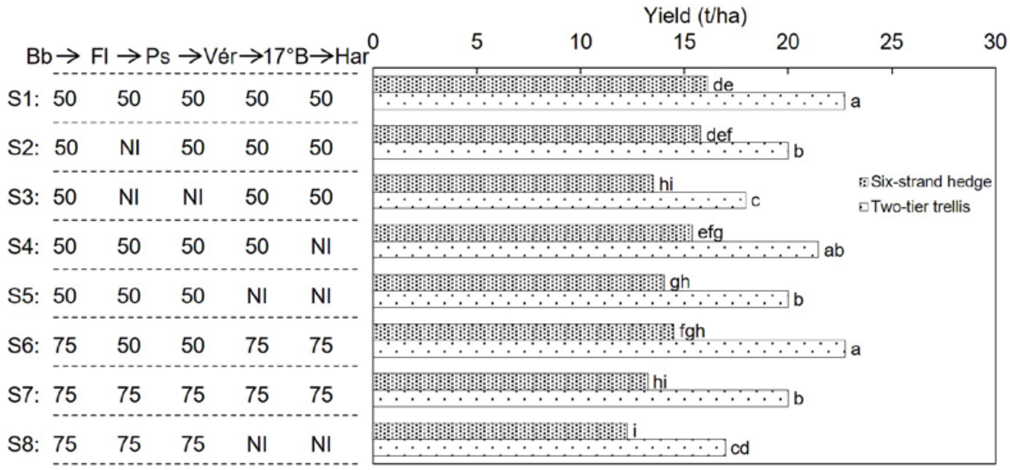

FIGURE 9
Effect of irrigation strategies (S) consisting of different levels of soil water depletion and no irrigation (NI) on yield of Pinotage/99R trained onto two different trellis systems near Robertson (Bb = budbreak; Fl = flowering; Ps = pea size; Vér = véraison & Har = harvest). Data are means for three years. Columns designated by the same letters do not differ (p ≤ 0.05).

TABLE 6
Effect of different irrigation strategies (S), i.e. combinations of 50% readily available water depletion (50), 75% readily available water depletion (75) and no irrigation (NI) between various phenological stages, namely budbreak (Bb), flowering (Fl), pea size berries (Ps), véraison (Vér), 17°B and harvest (Har) on total titratable acidity (TTA) of Pinotage/99R trained onto a six-strand hedge (6-Str hedge) and a two-tier trellis near Robertson in the Breede River Valley for the 1998/99, 1999/00 and 2000/01 seasons.

Irrigation strategy						TTA (g/L)					
						1989/99		1999/00		2000/01	
	Bb→	Fl →	Ps →	Vér →	17°B → Har	6-Str hedge	Two-tier	6-Str hedge	Two-tier	6-Str hedge	Two-tier
S1:	50	50	50	50	50	5.66 def[1]	5.70 def	9.37 ab	6.47 def	7.03 ab	5.40 cd
S2:	50	NI	50	50	50	6.37 cde	6.97 abc	6.63 def	5.87 f	6.93 ab	5.67 c
S3:	50	NI	NI	50	50	5.31 f	5.45 ef	7.60 cd	5.33 f	6.67 b	5.63 c
S4:	50	50	50	50	NI	6.33 cde	6.60 bcd	6.20 f	6.10 f	6.83 b	5.13 d
S5:	50	50	50	NI	NI	7.60 a	7.36 ab	9.20 ab	6.20 f	7.13 ab	5.67 c
S6:	75	50	50	75	75	7.63 a	5.22 f	10.17 a	6.27 ef	7.37 a	5.60 cd
S7:	75	75	75	75	75	6.00 def	6.03 cdef	8.40 bc	5.87 f	6.73 b	5.37 cd
S8:	75	75	75	NI	NI	6.03 cdef	5.98 def	7.57 cde	5.50 f	6.70 b	5.43 cd
Mean±1 std. dev.						6.37±0.84	6.16±0.75	8.14±1.39	5.95±0.39	6.92±0.24	5.49±0.19

[1] Values designated by the same letter within each season do not differ significantly (p ≤ 0.05).

by water deficits during berry ripening (S5 & S6) produced higher levels of juice TTA in grapes on the six-strand hedge compared to most of the other strategies over the three seasons (Fig. 10). A previous study also showed that post-véraison water constraints can increase juice TTA (Hardie & Considine, 1976). In the case of the two-tier trellis, irrigation strategy had no effect on juice TTA, except where irrigation at 50% PAW depletion which was terminated at véraison (S5) increased TTA compared to some of the other strategies (Fig. 10). On average, the juice TTA produced by grapevines of all irrigation strategy/trellis system combinations were within the typical range of 5 to 8 g/L for grapes (Rajković *et al*., 2007).

pH: In the 1998/99 season, trellis system had no effect on juice pH, except for the low pH in grapes produced on the six-strand hedge where 75% RAW depletion was changed to 50% depletion between flowering and pea size berries (S6) (Table 7). In the 1999/00 season, the trellis system had no effect on juice pH. In the 2000/01 season, the pH in juice produced on the two-tier trellis was higher compared to the six-strand hedge, except where irrigation at 50% RAW depletion was stopped from flowering to véraison (S3) and during berry ripening (S5). On average, irrigation strategy had no effect on juice pH, except that grapes produced on the six-strand hedge where irrigation at 50% RAW depletion

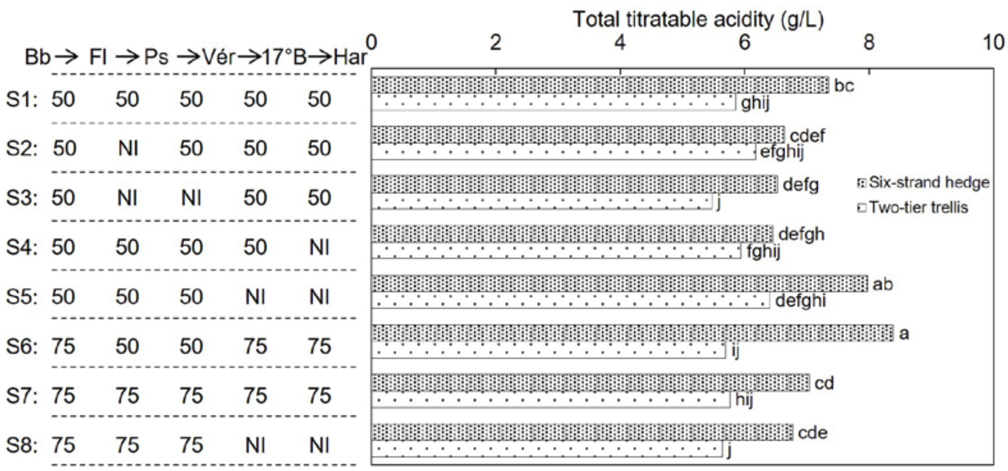

FIGURE 10
Effect of irrigation strategies (S) consisting of different levels of soil water depletion and no irrigation (NI) on total titratable acidity (TTA) of Pinotage/99R trained onto two different trellis systems near Robertson (Bb = budbreak; Fl = flowering; Ps = pea size; Vér = véraison & Har = harvest). Data are means for three years. Columns designated by the same letters do not differ ($p \leq 0.05$).

TABLE 7
Effect of different irrigation strategies (S), i.e. combinations of 50% readily available water depletion (50), 75% readily available water depletion (75) and no irrigation (NI) between various phenological stages, namely budbreak (Bb), flowering (Fl), pea size berries (Ps), véraison (Vér), 17°B and harvest (Har) on juice pH of Pinotage/99R trained onto a six-strand hedge (6-Str hedge) and a two-tier trellis near Robertson in the Breede River Valley for the 1998/99, 1999/00 and 2000/01 seasons.

Irrigation strategy						**Juice pH**					
						1989/99		**1999/00**		**2000/01**	
	Bb→	**Fl →**	**Ps →**	**Vér →**	**17°B → Har**	**6-Str hedge**	**Two-tier**	**6-Str hedge**	**Two-tier**	**6-Str hedge**	**Two-tier**
S1:	50	50	50	50	50	3.59 ab[(1)]	3.56 abc	3.23 a	3.20 a	3.28 hi	3.46 bcd
S2:	50	NI	50	50	50	3.49 bcd	3.47 cd	3.32 a	3.20 a	3.39 defg	3.59 a
S3:	50	NI	NI	50	50	3.63 a	3.58 abc	3.22 a	3.13 a	3.51 abc	3.57 a
S4:	50	50	50	50	NI	3.59 ab	3.56 abc	3.28 a	3.21 a	3.31 ghi	3.47 bcd
S5:	50	50	50	NI	NI	3.50 bcd	3.48 bcd	3.30 a	3.21 a	3.27 hi	3.36 efgh
S6:	75	50	50	75	75	3.13 e	3.57 abc	3.20 a	3.14 a	3.24 i	3.40 def
S7:	75	75	75	75	75	3.64 a	3.58 abc	3.21 a	3.14 a	3.38 defg	3.55 ab
S8:	75	75	75	NI	NI	3.50 bcd	3.42 d	3.23 a	3.16 a	3.32 fghi	3.45 cde
Mean±1 std. dev.						3.50±0.18	3.53±0.06	3.25±0.04	3.17±0.03	3.34±0.09	3.48±0.08

(1) Values designated by the same letter within each season do not differ significantly ($p \leq 0.05$).

 DOI: https://doi.org/10.21548/45-2-6531

was stopped from flowering to véraison (S3) had higher pH compared to some of the other strategies (Fig. 11). In contrast, juice pH was the lowest where 75% RAW depletion was changed to 50% depletion between flowering and véraison (S6). The foregoing agrees with previous studies which showed that irrigation strategies do not have major effects on juice pH (Hardie & Considine, 1976; Van Zyl, 1984b; Medrano *et al*., 2003; Santos *et al*., 2005; Myburgh, 2006; Acevedo-Opazo *et al*., 2010; Myburgh, 2011; Williams & Heymann, 2017; P´erez-Alvarez *et al*., 2021). It is also noteworthy that the juice pH for all the trellis system/irrigation strategy combinations was in the optimum range of 3.0 to 3.5 for winemaking (Kodur, 2011; Walker & Blackmore, 2012).

Blue water footprint and water use efficiency

The average WF_{blue} of the grapes (Table 8) produced with micro sprinkler irrigation was higher than the global value of 97 m^3/t proposed by Mekonnen and Hoekstra (2010). Since most vineyards are drip irrigated (Way, 2014) which generally require less water than micro sprinklers (Van Zyl & Van Huyssteen, 1988; Myburgh, 2012), the higher than global WF_{blue} was to be expected. Under the prevailing conditions, the WF_{blue} of grapes produced on the two-tier trellis was substantially lower compared to the six-strand hedge, irrespective of the level of RAW depletion (Table 8). This confirmed that is possible to reduce the WF_{blue} if the bearing capacity of grapevines is extended vertically. In doing so, more grapes can be produced with the same irrigation volume. Although yields were marginally lower, irrigation at 75% RAW depletion tended to reduce the WF_{blue} of grapes produced on both trellis systems compared to irrigation at 50% RAW depletion. Furthermore, the WF_{blue} of grapes produced on the two-tier trellis where irrigation was applied at 75% RAW depletion was 44% lower compared to the six-strand hedge where irrigation was applied at 50% depletion (Table 8). It should be noted that the 139 m^3/t WF_{blue} of grapes produced on the two-tier trellis was similar to 138 m^3/t reported for drip irrigated Cabernet Sauvignon grapes on a Scott Henry trellis with a vertically split canopy (Williams & Heymann, 2017). In the latter study, the WF_{blue} was only reduced when less irrigation caused a concomitant yield reduction. However, such an approach is certainly not an economically viable option to reduce the WF_{blue} of wine grapes.

Surprisingly, the WUE_i of the micro sprinkler irrigated grapevines on the six-strand hedge (Table 8) was comparable to 5.01 kg/m^3 (Mirás-Avalos *et al*., 2016), and even higher than 2.69 kg/m^3 (P´erez-Alvarez *et al*., 2021) reported for drip irrigated grapevines on vertical trellises. In contrast, the

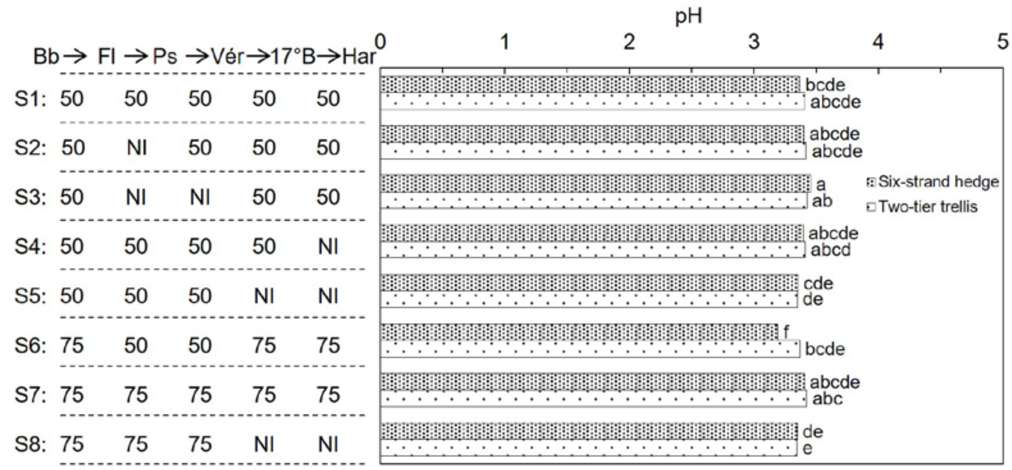

FIGURE 11

Effect of irrigation strategies (S) consisting of different levels of soil water depletion and no irrigation (NI) on pH of Pinotage/99R trained onto two different trellis systems near Robertson (Bb = budbreak; Fl = flowering; Ps = pea size; Vér = véraison & Har = harvest). Data are means for three years. Columns designated by the same letters do not differ ($p \leq 0.05$).

TABLE 8

Effect of readily available water (RAW) depletion budbreak to harvest and trellis system on the blue water footprint (WF_{blue}) and irrigation water use efficiency (WUE_i) of Pinotage/99R during the 2000/01 season near Robertson.

Strategy	RAW depletion	Trellis system	Irrigation (mm)	Yield (t/ha)	WF_{blue} (m^3/t)	WUE_i (kg/m^3)
S1	50%	Six-strand hedge	584	23.5	249	4.0
		Two-tier	584	31.6	185	5.4
S7	75%	Six-strand hedge	407	19.3	211	4.7
		Two-tier	407	29.2	139	7.2

WUE_i was appreciably lower than 10.4 kg/m^3 obtained with drip irrigated Merlot on a vertical trellis (Myburgh, 2011). In the case of the two-tier trellis, the WUE_i of grapevines was only slightly less than the 7.9 kg/m^3 of drip irrigated Thompson seedless grapevines on a horizontally orientated trellis system in the Breede River Valley (Myburgh & Howell, 2023). The WUE_i of grapes produced on the two-tier trellis where irrigation was applied at 75% RAW depletion was 78% higher compared to the six-strand hedge with irrigation applied at 50% RAW depletion (Table 8). Results confirmed that it is possible to increase the WUE_i, or reduce the WF_{blue}, substantially by producing more grapes with less irrigation water.

CONCLUSIONS

This was the first study where Pinotage responses to water deficits were determined. Vegetative growth of Pinotage was insensitive to water deficits during various stages, except where drier soil conditions prevailed from budbreak to harvest. The distribution of growth vigour over longer cordons on the two-tier trellis tended to reduce the primary shoot thickness. Consequently, the cane mass of grapevines on the two-tier trellis was unexpectedly lower compared to the six-strand hedge with shorter cordon arms. Pinotage berry mass was most sensitive to water deficits during the pre-véraison period, as well as continued water deficits from budbreak to harvest. This eventually reflected in the yield. In the case of the six-strand hedge, the average yield of grapevines that received the least irrigation was within the industry norms. Furthermore, water deficits did not have any detrimental effects on juice TTA and pH. This suggested that Pinotage can withstand a fair amount of water constraints. It also explains why Pinotage is one of the preferred cultivars for rain fed viticulture in the coastal region of the Western Cape. The best irrigation strategy for Pinotage is to avoid water constraints during the pre-véraison period. If irrigation water is limited, or when water restrictions are imposed during droughts, irrigation can be reduced, or even terminated during the post-véraison period. This study showed that it is possible to produce more grapes with the same volume of irrigation water by extending the bearing capacity of grapevines vertically. Furthermore, it was shown that it is also possible to produce more grapes with less water, and in doing so reduce the WF_{blue}, or increase the WUE_i, of wine grapes in a profitable way. If the two-tier trellis is to be considered as a means to increase grapevine yield, or to use irrigation water more effectively, it would be advisable to restrict the in-row plant spacing to 1.2 m, or probably even narrower in less fertile soil.

LITERATURE CITED

Acevedo-Opazo, C., Ortega-Farias, S. & Fuentes, S., 2010. Effects of grapevine (*Vitis vinifera* L.) water status on water consumption, vegetative growth and grape quality: An irrigation scheduling application to achieve regulated deficit irrigation. Agric. Wat. Manage. 97, 956-964.

Amerine, M.A. & Winkler, A.J., 1944. Composition and quality of musts and wines of California grapes. Hilgard 15, 493-673.

Araujo, J.A., Abiodun, B.J. & Crespo, O., 2014. Impacts of drought on grape yields in Western Cape, South Africa. Theor. App. Climatology. https://hal.science/hal-01161906.

Bruwer, R.J., 2010. The edaphic and climatic effects on production and wine quality of Cabernet Sauvignon in the Lower Olifants River region. Thesis, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa.

Conradie, W.J. & Myburgh, P.A., 2000. Fertigation of *Vitis vinifera* L. cv. Bukettraube/110R on a sandy soil. S. Afr. J. Enol. Vitic. 21, 40-47.

Coombe, B.G., 1995. Adoption of a system for identifying grapevine growth stages. Aust. J. Grape Wine Res. 1, 104-110.

De Villiers, F.S., Schmidt, A., Theron, J.C.D. & Taljaard, R., 1996. Subdivision of the Western Cape viticultural regions according to existing climate criteria (in Afrikaans). Wynboer Tegnies, January 1996, 10-12.

Fourie, J., 2021. Cover crops in South African vineyards. Agricultural Research Council, Pretoria, South Africa.

Goussard, P., 2008. Grape cultivars for wine production in South Africa. Cheviot Publishing, Cape Town, South Africa.

Hardie, W.J. & Considine, J.A., 1976. Response of grapes to water-deficit stress in particular stages of development. Am. J. Enol. Vitic. 27, 55-61.

Iland, P., 1989. Grape berry composition - the influence of environmental and viticultural factors. Part 2 - Solar radiation. Aust. Grapegrow. Winemaker, April 1989, 74-76.

Kliewer, W.M., 1971. Effect of day temperature and light intensity on concentration of malic and tartaric acids in *Vitis vinifera* L. grapes. J. Amer. Soc. Hort. Sci. 96, 372-377.

Klute, A., 1986. Water retention: laboratory methods. In Klute, A. (ed.). Methods of soil analysis. Part I, Physical and mineralogical methods. No.9, Agronomy series. Madison, Wis.

Kodur, S., 2011. Effects of juice pH and potassium on juice and wine quality, and regulation of potassium in grapevines through rootstocks (*Vitis*): A short review

Lategan, E.L., 2011. Determining of optimum irrigation schedules for drip irrigated Shiraz vineyards in the Breede River Valley. Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Lategan, E.L. & Howell, C.L., 2016. Deficit irrigation and canopy management practices to improve water use efficiency and profitability of wine grapes. WRC Report No. 2080/1/16. ISBN 978-1-4312-0816-6.

Le Roux, E.G., 1974. A climate classification for the South Western Cape viticultural areas (in Afrikaans). Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Ley, T.W., 1994. Irrigation system evaluation and improvement. In: Williams, K.M. & Ley, T.W. (eds). Tree fruit irrigation: A comprehensive manual of deciduous tree fruit irrigation needs. Good Fruit Grower, Yakima, Washington. pp. 203-221.

McCarthy, M.G., 1997. The effect of transient water deficit on berry development of cv. Shiraz (*Vitis vinifera* L.). Aust. J. Grape Wine Res. 3, 102-108.

Medrano, H., Escalona, J., Cifre, J., Bota, J. & Flexas, J., 2003. A ten-year study on the physiology of two Spanish grapevine cultivars under field conditions: effects of water availability from leaf photosynthesis to grape yield and quality. Func. Plant Biol. 30, 607-619.

Mekonnen, M.M. & Hoekstra, A.Y., 2010. The green, blue and grey water footprint of crops and derived crop products. Value of Water Research Report Series No. 47, UNESCO-IHE, Delft, the Netherlands.

Mirás-Avalos, J.M. Trigo-Córdoba, E., Bouzas-Cid, Y. & Orriols-Fernández, I., 2016. Irrigation effects on the performance of grapevine (*Vitis vinifera* L.) cv. 'Albarino' under the humid climate of Galicia. OENO One 50, 183-194.

Munitz, S., Netzer, Y. & Schwartz, A., 2017. Sustained and regulated deficit irrigation of field-grown Merlot grapevines. Aust. J. Grape Wine Res. 23, 87-93.

 DOI: https://doi.org/10.21548/45-2-6531

Myburgh, P.A., 1996. Response of *Vitis vinifera* L. cv. Barlinka/Ramsey to soil water depletion levels with particular reference to trunk growth parameters. S. Afr. J. Enol. Vitic. 17, 3-14.

Myburgh, P.A., 1998. Water use of South African vineyards: A modelling approach based on the quantified combined effects of selected viticultural, soil and meteorological parameters. Dissertation, University of Stellenbosch, Private Bag X1, Matieland 7602, South Africa.

Myburgh, P.A., 2003a. Possible flood irrigation technologies to reduce water use of Sultanina grapevines in a hot, arid climate. S. Afr. J. Plant Soil 20, 180-187.

Myburgh, P.A., 2003b. Responses of *Vitis vinifera* L. cv. Sultanina to level of soil water depletion under semi-arid conditions. S. Afr. J. Enol. Vitic. 24, 16-24.

Myburgh, P.A., 2003c. Responses of *Vitis vinifera* L. cv. Sultanina to water deficits during various pre- and post-harvest phases under semi-arid conditions. S. Afr. J. Enol. Vitic. 24, 25-33.

Myburgh, P.A., 2006. Juice and wine quality responses of *Vitis vinifera* L. cvs. Sauvignon blanc and Chenin blanc to timing of irrigation during berry ripening in the Coastal region of South Africa.

Myburgh, P.A., 2007. The effect of irrigation on growth, yield, wine quality and evapotranspiration of Colombar in the Lower Orange River Region. Wineland, Technical Yearbook 2007/08, 59-62.

Myburgh, P.A., 2008. The contribution of atmospheric humidity to yield fluctuations of Sultanina in the Lower Orange River region. Wynboer Technical Yearbook, 2008/9, 38-41.

Myburgh, P.A., 2011. Response of *Vitis vinifera* L. cv. Merlot to low frequency irrigation and partial root zone drying in the Western Cape Coastal Region - Part II. Vegetative growth, yield and quality.

Myburgh, P.A., 2012. Comparing irrigation systems and strategies for table grapes in the weathered granite-gneiss soils of the Lower Orange River Region. S. Afr. J. Enol. Vitic. 33, 184-197.

Myburgh, P.A., 2018. Handbook for irrigation of wine grapes in South Africa. Agricultural Research Council, Pretoria, South Africa.

Myburgh, P.A. & Howell, C.L., 2007. Evapotranspiration of *Vitis vinifera* L. cvs. Sunred Seedless and Muscat Supreme in response to soil water depletion and irrigation cutoff during berry ripening.

Myburgh, P.A. & Howell, C.L., 2023. Effects of soil ameliorants produced from recycled glass on the establishment of table grapes. S. Afr. J. Enol. Vitic. 44, 101-111.

Myburgh, P.A. & Van der Walt, L.D., 2005. Cane water content and yield responses of *Vitis vinifera* L. cv. Sultanina to overhead irrigation during the dormant period.

Myburgh, P.A., Van Zyl, J.L. & Conradie, W.J., 1996. Effect of soil depth on growth and water use of young *Vitis vinifera* L. cv. Pinot noir.

Peel, M.C., Finlayson, B.L. & McMahon T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci., 11, 1633-1644.

P´erez-Alvarez, E.P., Intrigliolo Molina, D.S., Vivaldi, G.A., García-Esparza, M.J., Lizama, V. & Alvarez, I., 2021. Effects of the irrigation regimes on grapevine cv. Bobal in a Mediterranean climate: I. Water relations, vine performance and grape composition. Agric. Wat. Manage. 248. https://doi.org/10.1016/j.agwat.2021.106772.

Rajković, M.B., Novaković, I.D. & Petrović, A., 2007. Determination of titratable acidity in white wine. J. Agric. Sci. 52, 169-184.

Santos, T.P., Lopes, C.M.. Rodrigues, M.L., De Souza, C.R., Ricardo-da-Silva, J.M., Maroco, J.P., Pereira, J.S. & Chaves, M.M., 2005. Effects of partial root-zone drying irrigation on cluster microclimate and fruit composition of field-grown Castelão grapevines. Vitis 44, 117-125.

SAWIS, 2023. South Africa wine industry statistics, www.wosa.co.za.

Smart, R.E., 1982. Vine manipulation to improve wine quality. Proc. Int. Symp. Grapes Wine, Davis, California, 1980, 362-375.

Soil Classification Working Group, 1991. Soil Classification - A taxonomic system for South Africa. Memoirs on natural agricultural resources of South Africa No. 15, Dept. of Agric. Develop., Private Bag X144, Pretoria, 0001 South Africa.

Stolk, R.A., 2014. The effect of irrigation and canopy management on selected vegetative growth and reproductive parameters of *Vitis vinifera* L. cv. Shiraz in the Breede River Valley.

Swanepoel, J.J., Hunter, J.J. & Archer, E., 1990. The effect of trellis systems on the performance of *Vitis vinifera* L. cvs Sultanina and Chenel in the Lower Orange River region.

Van Schalkwyk, D., 2004. Methods to determine berry mass, berry volume and bunch mass. Wineland, September, 111-112.

Van Zyl, J.L., 1984a. Interrelationships among soil water regime, irrigation and water stress in the grapevine (*Vitis vinifera* L.). Dissertation, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa.

Van Zyl, J.L., 1984b. Response of Colombar grapevines to irrigation as regards quality aspects and growth. S. Afr. J. Enol. Vitic. 5, 19-28.

Van Zyl, J.L. & Van Huyssteen, L., 1980. Comparative studies on wine grapes on different trellis systems: I. Consumptive water use. S. Afr. J. Enol. Vitic. 1, 7-14.

Van Zyl, J.L. & Van Huyssteen, L., 1988. Irrigation systems - Their role in water requirements and the performance of grapevines. S. Afr. J. Enol. Vitic. 9, 3-8.

Vilanova, M., Rodriguez-Nogales, J.M., Vila-Crespo, J. & Yuste, J., 2019. Influence of water regime on yield components, must composition and wine volatile compounds of *Vitis vinifera* L cv. Verdejo.

Walker, R.R. & Blackmore, D.H., 2012. Potassium concentration and pH inter-relationships in grapejuice and wine of Chardonnay and Shiraz from a range of rootstocks in different environments. Aust. J. Grape Wine Res. 18, 183-193.

Way, R., 2014. Irrigation drip system design for a vineyard. https://api.core.ac.uk/oai/oai: digitalcommons.calpoly.edu:braesp-1140.

Williams, L.E., Dokoozlian, N.K. & Wample, R., 1994. Grape. In: Schaffer, B. & Anderson, P.C., (eds). Handbook of environmental physiology of fruit crops, Vol. 1 Temperate Crops. Orlando, CRC Press. pp. 83-133.

Williams, L.E. & Heymann, H., 2017. Effects of applied water amounts and trellis/training system on grapevine water relations, berry characteristics, productivity and wine composition of "Cabernet Sauvignon". Acta Hortic. 1150, 413-426.

Wolf, T.K., Dry, P.R., Iland, P.G., Botting, D., Dick, J., Kennedy, U. & Ristic, R., 2003. Response of Shiraz grapevines to five different training systems in the Barossa Valley, Australia. Aust. J. Grape Wine Res. 9, 82-95.