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Response of grapevine (Cabernet Sauvignon cv) to above ground and subsurface drip irrigation under arid conditions

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ABSTRACT

The response of wine grapes to irrigation systems was investigated in a Cabernet Sauvignon/140 Ru vineyard in sandy loam soil in Sicily during a two-year study. Two different drip irrigation systems were evaluated: one surface drip and two subsurface drip irrigation systems, with the trickle line located at different distances from vine trunks. Vegetative and quantitative parameters, must quality and root distribution were compared among irrigation treatments. During the two study years, irrigation of grapevines via a subsurface drip system resulted in greater water use efficiency without affecting must composition. Establishing the trickle line near the trunk positively influenced trunk growth and total root contact while establishing the trickle line 1.20 m from the trunk increased yield. Dry mass partitioning was modified in subsurface irrigation treatments in favour of reproductive organs. We conclude that subsurface drip irrigation under the trunk can be successfully used under water deficit irrigation management, even in sandy loam soil and in the hot climate conditions of the Mediterranean vineyard. Some aspects of management deserve further investigation and further studies may better define the optimum conditions for the successful utilization of the SDI 120 irrigation strategy.

1. Introduction

Sicily is a region in southern Italy with a history of wine production. The climate is warm and arid, and farmers are thus faced with the problem of achieving high grape yields and good grape quality with limited water supply. Water use efficiency plays an important role in irrigation strategies, particularly considering the water scarcity in Mediterranean areas as a consequence of climate change (Tomás et al., 2014).

Irrigation method significantly affects yield, vegetative, quality components and root development as well as water use efficiency. Irrigation system choice by grape farmers should also include consideration of many variables, such as type, depth and uniformity of soil, rooting zone, availability and quality of water, and total cost (Myburgh, 2012).

The advantages of drip irrigation over sprinklers and other conventional irrigation systems (Van Zyl, 1988) for vegetative, reproductive and qualitative parameters in *Vitis vinifera* are well known but only in subsurface system (Striegel et al., 1996; Sharma et al., 2005; Myburgh, 2007a,b; Sharma and Upadhyay, 2011), and more in-depth investigations are required. Many researchers define subsurface drip irrigation as a method of dispensing water below the soil surface with the same emitters and discharge rates range as surface drip irrigation (Davis and Nelson, 1970; Camp and Lamn, 2003). Subsurface systems are an important component of lower pressure systems, although the literature present contrasting results of subsurface drip irrigation. Major issues mainly involve irrigation management, and more specifically as in all irrigation systems, establishing the optimal water dose and drip line depth and distance from the row for different crops (Ayars et al., 2015). The choice of the appropriate drip line depth is influenced by crop, soil and climate characteristics. Soil hydraulic properties and emitters discharge affect vertical water movement in the soil and thus are factors that should be considered in the choice of dripline depth. For perennial crops (trees and grapes), the dripline is typically installed at a depth of 12–20 inches; sandy soils allow shallower installation depth and regardeless of soil type, the dripline should be positioned in the upper portion of the root zone to prevent excessive drainage, among other effects (Lamm, 2009). Myburgh (2007a,b), in studies of a subsurface drip irrigation system in a layered alluvial soil, showed a lower concentration of roots around the drip lines located at depth of 15 cm compared with those at 30 and 45 cm, but without negatively influencing grape production and quality.

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Gaiotti (2010) in on a four-year old Merlot/161-49 vineyard, found that roots were deeper and better developed when the trickle line was positioned at 1.35 m from the vine row, whereas when positioned at 0.4 m, growth was shallower and denser, similar to that of surface drip irrigation, and resulted in higher grape production and vigour.

Subsurface drip irrigation is a system designed to improve water use efficiency (WUE) compared with surface drip irrigation systems. The usage of subsurface drip irrigation has always lead to an enhancement of crop yield and quality, a decreased water requirement and decreased costs for other cultural practices in annual crops (e.g., tomato, cotton, sweet corn, cantaloupe, garlic, broccoli, pepper, and lettuce) (Ayars et al., 1999) as well as in fruit crops and in some cases, nut crops. Long term research of subsurface drip irrigation needed, especially to better understand the potential uses in nut crops, fruit trees and vines as acknowledged by Ayars et al. (2015).

For nut crops such as almond and pistachio, subirrigation system are considered especially useful due to potential for water and energy savings, enhancement of pest management, and ultimately increased production and nut quality (Ayars et al., 2015). Moreover, in French prune orchards in the northern Sacramento Valley (CA), the subirrigation method is used to better support water infiltration in clay and silt loam soils compared to surface drip irrigation (Ayars et al., 2015).

Considering that Sicily is a region with a warm, arid climate and limited water supply, a change in irrigation strategy may become essential to save water in viticulture without reducing the profitability of grapevines. For this reason, the objectives of this study were to 1) investigate as an alternative the subsurface irrigation system, and to compare results to the standard surface drip irrigation system, the most common method in Sicily and 2) compare trickle line positioning at two different distances from the vine row within a subsurface drip irrigation system, placed under the vine row and in the middle of the interrow. The choice of distances of trickle line from vine row in subsurface drip irrigation was established to ensure the uniformity of root development on both side of the rows maintaining only one trickle line.

2. Materials and methods

2.1. Field conditions, plant material and irrigation treatments

The response of grapevines to two different irrigation systems was investigated during the 2004 and 2005 vegetative seasons in a nine-year old Cabernet Sauvignon/140 Ru experimental vineyard, planted in 1996. Planting distance was 2.4 × 0.95 m, row orientation was north-south, and vines were trellised in a vertical shoot-positioned system and, cane pruned (8 buds per cane and 2 buds per spur). The vineyard was located in Western Sicily (Mazara del Vallo area, 37°36′10.93″ N – 12°39′15.26″ E, 34 m a.s.l.) in 80 cm deep soil characterized by 10% gravel, 20.8% clay, 35.2% silt and 44% sand. Soil management practices included a cover crop (*Vicia Faba*) during winter and incorporating the biomass into the soil in April by ploughing. Three shallow tillages (10–12 cm deep) from spring to summer were adopted to control weeds and prevent soil cracking (Crescimanno and Garofalo, 2006). During the two years of this trial, weather data were collected through an automated weather station at the Servizio Informativo Agrometeorologico Siciliano, 2017 (www.sias.regione.sicilia.it) located near the vineyard.

Three irrigation treatments with the same drip line emitter configuration, were investigated:

1 Surface drip irrigation (DR) with one drip line at 0 cm from the vine row and 50 cm above the soil, fixed on a dedicated wire below the cane;
2 Subsurface drip irrigation with one drip line at 0 cm from the vine row (under the vine) and 0.35 m deep (SDI 0);
3 Subsurface drip irrigation with one drip line at 1.20 m, positioned equidistantly between adjacent vine rows and 0.35 m deep (SDI 120).

The drip line was mechanically installed before vineyard establishment, deep enough (0.35 m) to prevent damage by tillage, but sufficiently shallow to supply water to the root zone (Van Huyssteen and Weber, 1980) without wetting the soil surface (Camp and Lamn, 2003).

Surface and subsurface methods entailed a drip line irrigation system with pressure compensating emitters with a flow rate of 4 L/hour were located one metre apart. The amount of water applied in each treatment was measured using flow meters.

2.2. Irrigation scheduling

The time of irrigation was determined physiologically by measuring plant water status through leaf water potential at various stages during the trial, including the harvest stage. These measures were taken at predawn using a Scholander pressure chamber (model 3115 Soilmoisture Equipment Corp. Santa Barbara, CA) on 3 fully expanded leaves from primary stems per block and treatment.

Irrigation for all treatments was managed by using a threshold predawn leaf water potential (ψ_{pd}) of −0.4 MPa from berry set to the end of veraison and −0.6 MPa from the end of veraison (Di Lorenzo et al., 2005). In both years, irrigation was stopped 15 days before the probable harvest date.

Optimum irrigation volumes were calculated based on data gathered in the same vineyard from an experimental trial performed in parallel to this experiment, aimed characterizing soil moisture profiles using FDR probes (Provenzano et al., 2016). In particular, at each irrigation date, the volumes of water administered were regulated to reach field capacity within soil zone wetted by the emitters and the soil layers most populated by roots while avoiding deep percolation. Field capacity and wilting point were determined using Richard's plates (Richards, 1947). The amount of water was reduced by 20% in SDI treatments to account for the lower evaporation from the soil (Allen et al., 1998). This latter term was calculated as the ratio between f_w (fraction of the surface wetted) and f_c (fraction of ground surface coverage), with $f_c = 0.20$ and $f_w = 0.04$, considering a diameter of the wetted zone under the emitters equal to 0.23 m. Therefore, irrigation volume at each event was 75 m^3/ha in DR and 60 m^3/ha in SDI. ψ_{pd} was considered as a stress indicator and fluctuation of this variable between irrigations for all treatments, was measured in 2004 at +1, +3, +5 and +7 days after irrigation in two periods, once from fruit set to veraison and once from the end of veraison to harvest.

2.3. Experimental design

The experimental design consisted of three randomized complete-blocks, each with 9 rows 95 m in length with 100 vines. Within each block, each irrigation treatment was imposed on 3 contiguous rows. For each treatment and block, observations were performed on 15 vines of the central row, leaving the other two as buffer rows, to separate irrigation treatments.

2.4. Phenology

Data on the occurrence of budburst, flowering, beginning of veraison (20%), end of veraison and harvest dates for all treatments in 2004 and 2005 were recorded (Baggiolini, 1952). The budburst (stage C) and flowering stages (I) were considered to occur when

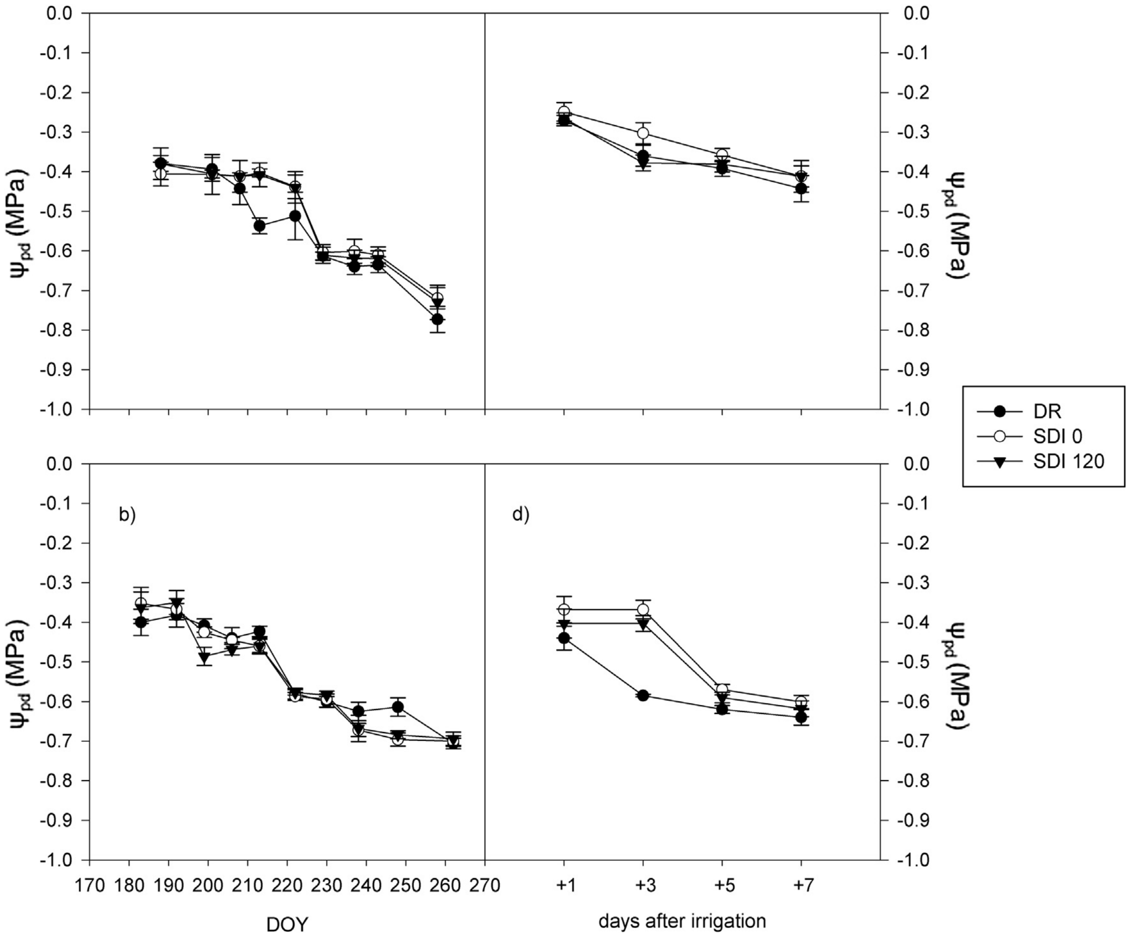

Fig. 1. Variation in predawn leaf water potential (MPa) values measured on DR, SDI 0, SDI 120 irrigation systems: a) the day before each irrigation during the trial in 2004; b) the day before each irrigation during the trial in 2005; c) +1, +3, +5 and +7 days after irrigation from fruit set to veraison in 2004; d) +1, +3, +5 and +7 days after irrigation from veraison to harvest in 2004.

50% of buds and flowers (respectively) showed the same phenological stage.

After veraison about 200 berries were weekly randomly picked and 30 days after veraison, more frequently (every 4 days) from vines of each irrigation treatments and replicates to measure total soluble solids (TSS) and titratable acidity (TA) (Jackson and Lombard, 1992), useful to define harvest time (stage N). When TSS did not increase for two subsequent measurements and TA was not lower than 5 g L^{-1}, grapes were harvested.

2.5. *Leaf area, pruning mass and trunk diameter*

Leaf area of primary and lateral shoots was measured at veraison and harvest using an image analysis system (WinDIAS; Delta-T Devices, UK), and 5 shoots per block and treatment (Barbagallo et al., 1996). Pruning mass was measured in winter in all marked vines (45 per treatment). Trunk circumference at 35 cm from the soil was assessed by a measuring tape after rhytidome removal at the beginning and at the end of the trial (March 2004-March 2006) on 75 vines per treatment (25 per block and treatment). Trunk diameter (d) was calculated by the formula d = circumference/π.

2.6. *Root system*

2.6.1. *Root number and distribution – trench profile technique*

Root evaluation was performed in February 2006 using the trench profile technique (Böhm, 1979). Trenches with 0.8 m depth, 2.0 m length and 0.6 m width were dug parallel to the rows to expose half of the root system of two vines. For each irrigation treatment, two trenches, i.e., two vines, were analysed. Trenches were sequentially dug at three distances from the trunk 1.2, 0.6 and 0 m. More specifically, the first trench was dug at 1.2 m from the vine, then after root measurements, the second (0.6 m) and the third (0 m) trenches were dug in the same location refining the existing trench at the fixed distances (Fig. 1). A thin layer of soil (1–2 cm) was carefully removed from the wall along the entire trench and visible roots (diameter ≤2 mm, and ≥2 mm) were painted with white varnish to enhance the colour contrast between the roots and the soil. A 1.5 m × 0.8 m wire-iron frame with a grid of 0.1 m × 0.1 m was pressed into the trench wall, and root contacts were counted and expressed as the number of root interceptions per dm^2 and as percentage of incidence of fine (<2 mm), medium and large (≥2 mm) roots. Hence, 360 grids per treatment were analysed (8 × 15 grids per frame, and three distances from trunk).

2.6.2. *Root length density (RLD), total length and surface:the core-break method*

Root length density (RLD, cm root/cm^3 soil) was measured, for each treatment, as follows: six 1000 cm^3 samples of soil (within the layer from 0.30 to 0.60 m depth) were randomly selected from the three trench walls (at 0, 0.60 and 1.20 m from the trunk) using a cylindrical core. A total of 18 soil samples were analysed per treatment. Roots from soil samples were classified according to their diameter as fine (less than 2 mm), medium (between 2 and 3.5 mm) and large (larger than 3.5 mm); total root length per soil sample and per root class was also determined. Root surface was

Table 1
Long term monthly climatic average for temperature (T), rainfall and estimated ETo[a] in Mazara del Vallo, Trapani, Sicily, South Italy.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
year 2004													
Mean max T (°C)	10.1	11.3	12.5	19.8	23.2	29.0	32.3	32.3	24.2	26.9	15.0	7.9	
Mean min T (°C)	4.6	5.8	7.6	11.5	11.1	14.9	17.6	18.2	13.1	14.9	9.8	6.2	
Rainfall (mm)	44.8	18.6	146.8	50.8	13.4	21.6	9.2	0.6	65.0	74.2	170.6	287.2	902.8
ET_o	25.0	46.7	63.1	82.7	111.3	133.1	153.2	136.0	101.9	73.5	41.5	29.4	997.4
year 2005													
Mean max T (°C)	9.6	8.6	12.2	19.6	26.3	29.4	32.8	30.5	28.9	25.3	14.7	10.9	
Mean min T (°C)	4.1	4.1	6.9	10.3	12.5	15.5	17.8	18.0	16.4	13.6	9.3	5.9	
Rainfall (mm)	91.4	85.0	33.6	101.4	7.6	7.6	8.6	6.8	9.6	111.0	92.8	89.8	645.2
ET_o	33.5	37.4	67.8	77.4	119.1	135.8	152.2	128.5	99.7	70.9	45.5	29.9	997.7

[a] Penman-Montheith method (Allen et al., 1998).

calculated by multiplying root diameter (average per class, i.e., 1 mm per class fine roots; 2.75 mm per class medium roots; 5 mm per class large roots) × π × total root length present in 1.000 cm^3 of soil. Root surface per vine was calculated by multiplying the root surface in 1.000 cm^3 of soil × soil volume available per vine (2.4 m × 0.7 m × 0.95 m) (Böhm, 1979).

2.7. Grape yield and quality

Data are reported from the 2004 and 2005 vegetative seasons. Shoot fruitfulness in 2005 and 2006 was assessed on the same vines observed in the previous year.

At harvest, in all vines (45 per treatment) the productive parameters were determined: yield, cluster number and weight. Berry weight and total anthocyanins (expressed as mg per berry) (Di Stefano and Cravero, 1991) were measured from a sample of 50 berries per block and treatment. The skins of each sample were separated from the pulp and placed in a flask containing 25 mL of tartaric buffer (pH 3.2) (500 mL of distilled water, 5 g of tartaric acid, 22 mL of 1 N NaOH, 2 g of sodium metabisulphite and 120 mL ethanol 95%). The volume of buffer was adjusted to 1 L by with distilled water. Skins were placed in the buffer for four hours at room temperature prior to homogenization and centrifugation. The supernatant was collected in a 100 mL volumetric flask, the residue was washed again with tartaric buffer (pH 3.2) added to the volumetric flask and the volume was raised to 100 mL with tartaric buffer (pH 3.2). The extract (10 mL) was diluted 25 times with acidified ethanol (ethanol, H_2O and concentrated HCl, 70:30:1 v/v/v), and absorbance was read at 540 nm using a UV–vis spectrophotometer (Varian Cary 50 Bio UV–vis Spectrophotometer, McKinley Scientific, Sparta, New Jersey, USA). From these values, estimates of total anthocyanins per berry (content) and mg per fresh weight of grape (concentration) were calculated.

Total Soluble Solids-TTS (Brix) were measured from 1 kg samples of grapes per block and treatment using an Atago PR-32 digital refractometer (Atago, Tokyo, Japan) and Titratable Acidity was measured from the same samples using a Crison Compact Titrator (Crison Instruments, Barcelona, Spain) by titration (0.1N NaOH) to pH 7 (expressed in g L^{-1} of tartaric acid).

2.8. Vine balance and water use efficiency

From each block and treatment, yield to pruning weight ratio (kg kg^{-1}) and total leaf area at harvest to yield ratio (m^2 kg^{-1}) were calculated. To evaluate the dry mass percentage distribution, grape and wood dry matter per shoot were calculated on the basis of the dry weight ratio to fresh weight determined, on oven-dried samples (Calò et al., 1999), separately for bunches and shoots.

Water use efficiency was quantified considering the yield (WUE_y) and the fresh biomass (WUE_b) (grapes, shoots and leaves) produced per total water amount in t ML^{-1} (rainfall from budburst to harvest plus irrigation).

The following above-to-belowground growth ratios were calculated only for 2005: yield-to-root surface ratio (kg m^{-2}), wood mass-to-root surface ratio (kg m^{-2}), and yield plus wood mass-to-root surface ratio (kg m^{-2}). In detail, for all these ratios, yield and wood mass values on a per-vine basis were divided by the average root surface per vine determined by the two trenches excavated for each treatment as detailed in paragraph 2.6.

2.9. Statistical analysis

Data describing vegetative and quantitative parameters and grape quality values were analysed separately by year. Comparisons of irrigation treatment groups were performed with Tukey's HSD test at $p < 0.05$. For fine root contacts (<2 mm diameter) comparisons of irrigation treatment groups were performed with Tukey's HSD test at $p < 0.05$, for each distance and depth. Arc sine square root transformation was used for proportions.

The correlation between root contact (trench profile technique) and root surface (core-break method) was evaluated using a Pearson correlation analysis.

Statistical analyses were run using the SYSTAT statistical software package (ver.10; Systat Software Inc., San Jose, CA).

3. Results

3.1. Climatic data

Weather data for the two years (2004 and 2005) are reported in Table 1. Total rainfall during the two seasons showed a high variability, with 902.8 mm in 2004 and 645.2 mm in 2005; the most significant differences were observed in autumn and winter. Particularly, rainfall before budburst was higher in 2005 than in 2004 (310.8 mm and 216.0 mm respectively), while the lowest rainfall was recorded from budburst to end of veraison in 2005. Late in the season, between the end of veraison and harvest in 2004 was drier than the same period in 2005 (Table 2). The highest precipitation was recorded in September 2004 after harvest (data not shown). In the two summers, there was little differences in maximum and minimum temperatures in June and July. August 2004 was hotter than August 2005 and September 2005 was hotter than September 2004. Winter was warmer in 2004 (Table 1). ET_0 calculated from budbreak to harvest did not differ between the two years (661.1 mm and 651.2 in 2004 and 2005 respectively) (data not shown).

3.2. Phenology

Since irrigation system did not affect vine phenology, data are reported as the average of all treatments (Table 2). The earlier bud-

Table 2
Days of the year (DOY) of phenological stages, rainfall at different period (mm), irrigation supplied to different irrigation treatments (mm), total water amount (mm) and irrigation dates (DOY) per each year.

year	2004	2005
Phenological stages[a] (DOY)		
Budburst	95	104
Flowering	145	147
Beginning Veraison	215	219
End Veraison	224	225
Harvest	258	262
Rainfall (mm) from:		
1th of January-Budburst	216	310.8
Budburst-Flowering	58.2	8.2
Flowering-End of Veraison	31.6	17.0
End of Veraison-Harvest	8.0	27.8
Budburst-Harvest	97.8	53.0
Irrigation supplied (mm) to:		
DR[b]	60.0	67.5
SDI 0	48.0	54.0
SDI 120	48.0	54.0
Total water amount (mm) to:		
Rainfall[c] + Irrigation in DR	157.8	120.5
Rainfall + Irrigation in SDI 0	145.8	107.0
Rainfall + Irrigation in SDI 120	145.8	107.0
Irrigation dates (DOY)	188, 201, 208, 213, 222, 229, 237, 243	183, 192, 199, 206, 213, 222, 230, 238, 249

[a] average of all treatments.
[b] DR (Surface drip irrigation with one drip line at 0 cm from the vine row); SDI 0 (Subsurface drip irrigation with one drip line at 0 cm from the vine row (under the vine); SDI 120 (Subsurface drip irrigation with one drip line at 1.20 m from the vine row.
[c] from budburst to harvest.

break in 2004 compared to 2005 (nine days before) was likely determined by the warmer winter. Differences in phenological stages were maintained until harvest (five days earlier in 2004) (Table 2).

3.3. Predawn water potential, irrigation dates and amounts

Irrigation began on the 6th of July in 2004 and the 2nd of July in 2005 when the ψ_{pd} reached approximately −0.4 MPa (Fig. 1a & b). The earlier starting point for irrigation in 2005 was due to having a drier period from budburst to flowering (Table 2). Rainfall between the first and the second irrigation (data not reported) induced a delay in water supply in both years (Table 2 and Fig. 1a & b). Subirrigation treatments (SDI 0, SDI 120) received 480 m^3/ha and 540 m^3/ha in 2004 and 2005, respectively, whereas 600 m^3/ha and 675 m^3/ha were applied to DR in 2004 and 2005, respectively.

After irrigation, ψ_{pd} showed a daily decrease from about 0.2 MPa to reach the 0.4 MPa threshold in the pre veraison period (Fig. 1c) and from 0.4 MPa to the 0.6 MPa threshold in the post veraison period (Fig. 1d). In all cases, the ψ_{pd} thresholds were attained in seven days both for the pre veraison and the post veraison irrigation regimes.

Vines in SDI treatments, even after receiving 20% less water than the DR treatment, showed similar water stress values measured in terms of ψ_{pd}. At harvest, irrigation treatments showed similar ψ_{pd} values for both years (Fig. 1a & b).

3.4. Vegetative parameters

Irrigation treatments showed no significant differences in main and lateral leaf area per shoot at veraison in 2004 and 2005. For main and lateral leaf abscission during the veraison-harvest period in SDI 0 and SDI 120, the differences became significant at harvest. Especially in SDI 120 a reduction of leaf area was registered in both years in main (44% and 40% respectively) and lateral shoots (37% and 57%). However, the irrigation treatments did not affect wood weight at pruning (Table 3).

3.5. Root system: number, distribution, length and surface

Both trench profile and core-break were effective for measuring root systems, and values of root contacts and root length were significantly correlated ($R^2 = 0.87$) (Fig. 2).

Roots were significantly affected by irrigation system, with differences in quantity ($n\,dm^{-2}$), type (fine, medium and large) (Table 4) and growth (either horizontally or vertically) (Fig. 3a & b). Surface drip irrigation resulted in a higher density of root contacts ($n\,dm^{-2}$) and incidence of fine roots compared to the subsurface systems (Table 4).

Fine roots decreased from row to interrow, except for in SDI 120 (Fig. 3a), where the trickle line was positioned. Fine roots were more abundant near the trunk in the surface drip system, whereas in all subirrigated treatments, they were higher near the trickle line (Fig. 3a). Furthermore, fine root development followed water movement in sandy soil in the surface drip irrigated treatment, resulting in a deeper root system compared to subirrigated vines (Fig. 3b), which remained more gathered near the trickle line.

The root surface per vine was higher in the surface drip irrigation system (6.03 m^2 $vine^{-1}$) than in the SDI 0 (4.67 m^2 $vine^{-1}$) and SDI 120 (3.96 m^2 $vine^{-1}$) irrigation systems, and the DR treatment showed a higher incidence of fine roots (<2 mm) (data not shown).

3.6. Grape yield and quality

Irrigation system considerably influenced yield per vine, bunch and berry mass (Table 5) but did not affect shoot fruitfulness (data not shown). In all treatments, yield decreased from the 2004 to 2005 vintage, and shoot fruitfulness increased from 2005 to 2006. Grape productivity was enhanced by subsurface drip irrigation, especially when the trickle line was positioned more distant from the vine row; SDI 120 showed a 44% yield greater than DR in 2004 and 49.7% greater yield in 2005 (Table 5). Cluster weight in DR and SDI 0 was lower than in SDI 120; and SDI 0 did not differ in cluster weight in either year. Water applied in the inter-row area (SDI 120) appeared to have a positive and significant effect on bunch mass. Differences in cluster weight were due to the higher berry weight in SDI 120. Reductions in berry weight were especially evident in the DR treatment (Table 5). In all treatments, clusters had a lower number of berries in 2005 than in 2004. This reduction in berry numbers can probably be ascribed to the higher temperatures during flowering, particularly during May, and higher temperature in 2005. These weather conditions probably modified the setting, reducing the number of berries per cluster (May, 2004). Number of berries did not significantly differ among treatments in either year (data not shown). Additionally irrigation treatment started every year after setting, and this did not influence the setting process.

Grape qualitative parameters were partially affected by irrigation treatment. Sugar level in 2004 was higher in inrow irrigated vines (DR and SDI 0) than in interrow vines (SDI 120). A significant difference was found only between SDI 0 and SDI 120 (Table 5). In 2005, higher sugar level was found in DR, but the differences were not significant between treatments. The highest soluble solid value in both years was 22.4 Brix combined with lower titratable acidity. For both the 2004 and 2005 seasons, a higher titratable acidity was found where higher yields per vine were observed; SDI 120 had the highest values during 2004 and 2005, and these values significantly different from SDI 0 in 2004 and DR in 2005 (Table 5).

Irrigation treatment had also significant effects on anthocyanins expressed per berry with the highest anthocyanin values observed

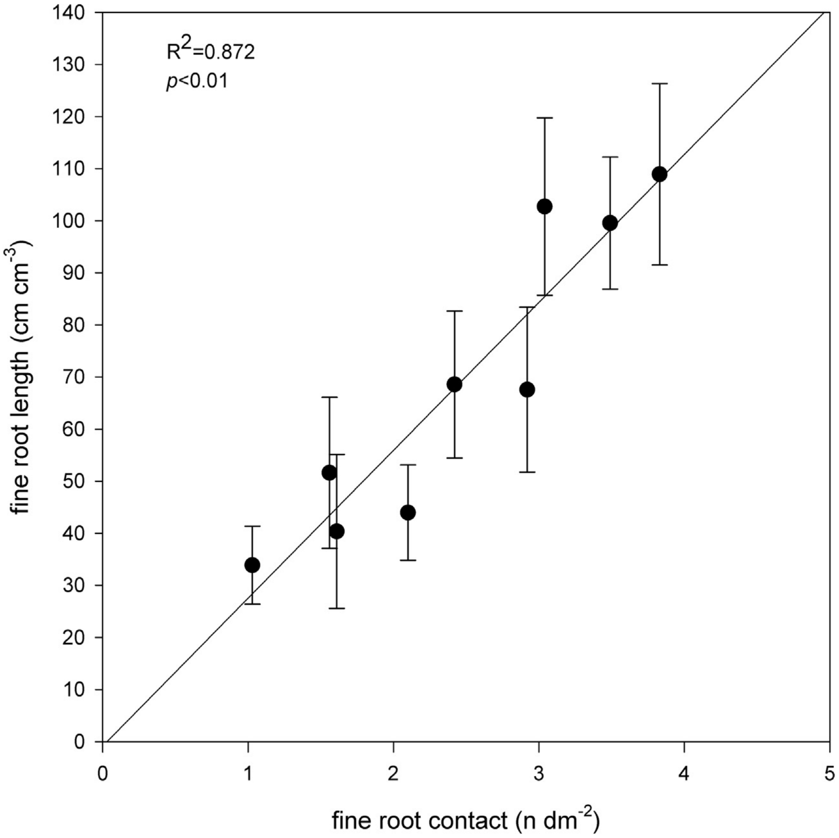

Fig. 2. Correlation between fine root length (cm cm^{-3}) measured through the "core-break method" and fine root contact (n dm^{-2}) measured through the "trench profile technique". Coefficient of determination (R^2) is reported. Each point represents the average of combinations, irrigation system and distance from row. Vertical bars indicate ± standard errors (n = 18).

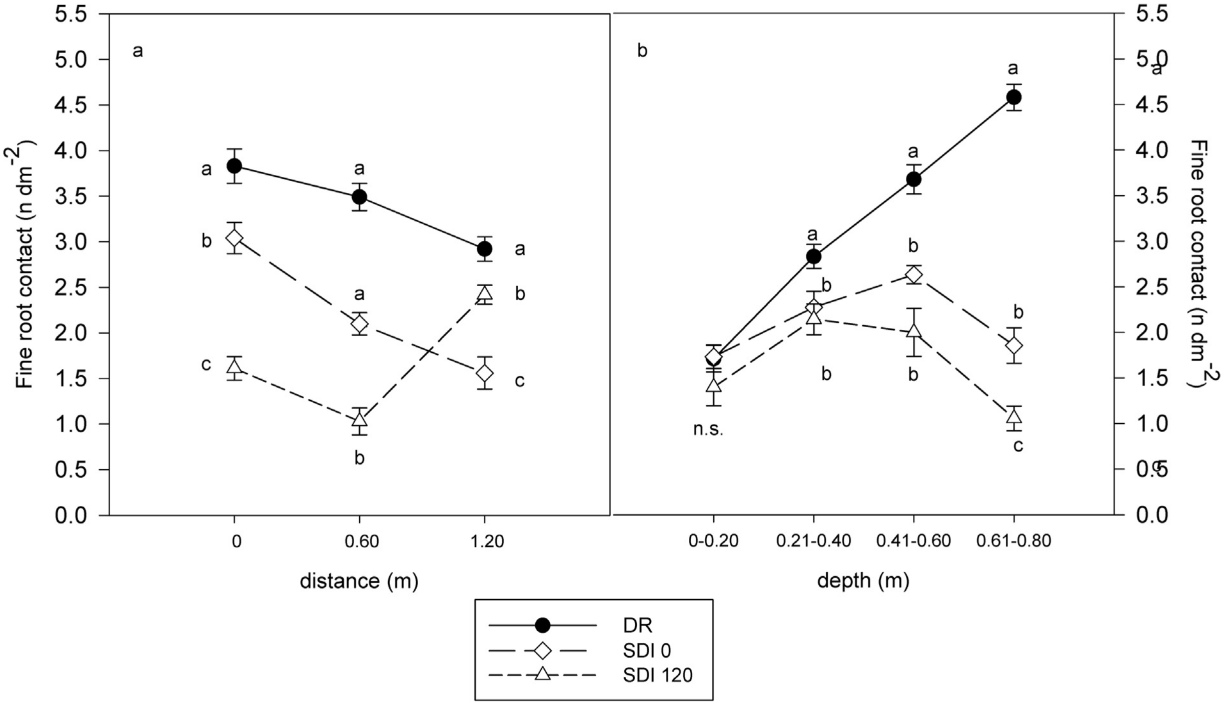

Fig. 3. a) Fine root contacts (n dm^{-2}) at 0 m, 0.60 m and 1.20 m distances from the row for DR, SDI 0, and SDI 120 irrigation systems. Vertical bars indicate ± SE (n = 40). b) Fine root contacts (n dm^{-2}) at different soil depths (0–0.20, 0.21–0.40, 0.41–0.60, 0.61–0.80 m) for DR, SDI 0, and SDI 120 irrigation systems. Vertical bars indicate ± standard errors (n = 30).
Within each distance (a) and within each depth (b), lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments according to Tukey's HSD test. n.s. = not significant.

Table 3
Vegetative characteristic in Cabernet Sauvignon grapevines, subjected to different irrigation systems DR, SDI 0 and SDI 120: main and lateral leaf area at veraison and harvest, pruning wood in 2004 and 2005. Values are means ± standard errors.

Year	Treatment/ Variable	Leaf area/ main shoot (cm^2) – veraison	Leaf area/ lateral shoot (cm^2) – veraison	Leaf area/ main shoot (cm^2) – harvest	Leaf area/ lateral shoot (cm^2) – harvest	Wood (kg vine^{-1})
2004	DR	$2281^{n.s.} \pm 260$	$1925^{n.s.} \pm 338$	$1854^{ab} \pm 243$	$1694^{n.s.} \pm 254$	$0.67^{n.s.} \pm 0.06$
	SDI 0	2865 ± 316	1867 ± 346	$2355^{a} \pm 185$	1175 ± 213	0.79 ± 0.06
	SDI 120	2704 ± 641	1498 ± 167	$1517^{b} \pm 133$	949 ± 267	0.70 ± 0.04
2005	DR	$2418^{n.s.} \pm 124$	$1464^{n.s.} \pm 281$	$2447^{a} \pm 166$	$1681^{n.s.} \pm 597$	$0.75^{n.s.} \pm 0.04$
	SDI 0	2683 ± 347	1351 ± 293	$2072^{ab} \pm 200$	1353 ± 532	0.78 ± 0.06
	SDI 120	2433 ± 267	1855 ± 315	$1466^{b} \pm 107$	801 ± 310	0.82 ± 0.05

Within year, lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments according to Tukey's HSD test, n.s. = not significant

Table 4
Total root contact (n dm^{-2}) and percentage of incidence of fine (< than 2 mm), medium and large (≥ than 2 mm) roots in Cabernet Sauvignon grapevines subjected to different irrigation systems: DR, SDI 0 and SDI 120. Values are means ± standard errors.

Year	Treatment/Variable	Total root (n dm^{-2})	Root <than 2 mm (%)	Root ≥than 2 mm (%)
2005	DR	$3.66^{a} \pm 0.22$	$88.05^{a} \pm 4.20$	$11.95^{a} \pm 4.20$
	SDI 0	$2.63^{b} \pm 0.17$	$84.91^{b} \pm 3.98$	$15.09^{b} \pm 3.98$
	SDI 120	$2.27^{b} \pm 0.19$	$74.27^{b} \pm 4.10$	$25.73^{b} \pm 4.10$

Within column, lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments according to Tukey's HSD test, n.s. = not significant.

Table 5
Productive and qualitative characteristics at harvest in Cabernet Sauvignon grapevines in 2004 and 2005 subjected to different irrigation systems DR, SDI 0 and SDI 120: yield (kg vine^{-1}), cluster weight (g); berry weight (g), total soluble solids (TSS) (°Brix), titratable acidity (g L^{-1}), anthocyanin content (mg berry^{-1}). Values are means ± standard errors.

Year	Treatment/Variable	Yield (kg vine^{-1})	Cluster wt (g)	Berry fresh wt (g)	TTS (°Brix)	Titratable acidity (g L^{-1})	Total anthocyanins (mg berry^{-1})
2004	DR	$1.87^{b} \pm 0.14$	$104.9^{b} \pm 7.75$	$0.76^{b} \pm 0.04$	$21.20^{ab} \pm 0.08$	$5.28^{n.s.} \pm 0.12$	$0.56^{ab} \pm 0.02$
	SDI 0	$2.14^{ab} \pm 0.15$	$120.1^{ab} \pm 8.52$	$0.87^{b} \pm 0.04$	$21.95^{a} \pm 0.12$	5.10 ± 0.08	$0.51^{b} \pm 0.01$
	SDI 120	$2.70^{a} \pm 0.16$	$151.8^{a} \pm 7.49$	$1.10^{a} \pm 0.02$	$20.30^{b} \pm 0.16$	5.87 ± 0.02	$0.63^{a} \pm 0.03$
2005	DR	$1.51^{b} \pm 0.16$	$101.1^{b} \pm 7.49$	$1.31^{b} \pm 0.02$	$22.40^{n.s} \pm 0.23$	$4.98^{b} \pm 0.08$	$0.42^{b} \pm 0.01$
	SDI 0	$1.77^{ab} \pm 0.14$	$112.3^{ab} \pm 9.81$	$1.36^{b} \pm 0.01$	21.97 ± 0.29	$5.18^{b} \pm 0.06$	$0.43^{b} \pm 0.01$
	SDI 120	$2.25^{a} \pm 0.13$	$142.3^{a} \pm 9.81$	$1.45^{a} \pm 0.01$	21.33 ± 0.29	$5.55^{a} \pm 0.05$	$0.48^{a} \pm 0.01$

Within year, lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments according to Tukey's HSD test, n.s. = not significant

in SDI 120 (Table 5), which significantly different from DR and SDI 0; however, there were no differences in anthocyanins expressed in mg kg^{-1} of grapes (data not shown).

3.7. *Dry mass and trunk diameter*

Total dry mass was higher in the treatments in which water was applied in the subsoil. Dry mass partitioning differed between the two subirrigated treatments; specifically, it was preferentially allocated to the reproductive parts when water was applied in the inter-row area (SDI 120) (Table 6). When the water supply was near the vine (DR and SDI 0), the highest seasonal trunk growth (percentage) was recorded between March 2004 and March 2006 (Table 6). It appeared that trunk growth was mainly dependent on the yield per vine and leaf fall. When leaf fall per shoot and yield per vine were higher, reduced trunk growth was observed and *vice versa* (Tables 3, 5 and 6).

3.8. *Vine balance*

The total leaf area/yield ratio was lower in SDI 120 than in DR in both years (Table 7) because of lower yield and higher leaf area per vine (data not shown) in DR. On the contrary in 2004, the highest values for the yield to pruning weight ratio per vine were observed in SDI 120 (Table 7), when the highest yield per vine was registered (Table 5), while difference among treatments were less pronounced in 2005. Aerial biomass and root surface index values were highest in the SDI 120 treatment (Table 8).

3.9. *Water use efficiency*

WUE$_y$ was generally higher in subsurface irrigation (SDI 0 and SDI 120) compared to DR treatments coherently with the lower irrigation volumes administered. Furthermore, the higher yield values observed in SDI 120 (Table 5) may have contributed to further increase WUE. At plant level (WUE$_b$) minor (2005) or no differences (2004) observed among treatments can be related to the compensating effect of the larger vegetative biomass (Table 3) observed in DR and SD 0 relative to SDI 120. This is in agreement also with the larger leaf area per unit of grape yield observed in DR and SD 0 in both years (Table 7).

4. Discussion

Results from our study showed that subsurface irrigation systems reduced water supply and increased yield without influencing grape quality. Many contrasting results are reported in the literature regarding the productive, qualitative and vegetative responses of vines to subsurface drip irrigation versus surface drip irrigation systems. In fact, Myburgh (2007b) found no advantages in terms of the amount of irrigation, yield and berry mass, using subsurface irrigation compared to a drip system, perhaps because the field trial was carried out in a table grape vineyard (Sultanina/143B Mgt) in an alluvial soil along the Lower Orange River, with an application of 7.000 m^3/ha irrigation water. In cv. “Godello”, a grapevine cultivar native to Galicia, no statistically significant differences were detected in yield and number of clusters per vine among subsurface

Table 6
Dry mass per shoot, dry mass percentage distribution between grape in 2004 and 2005 and differences in percentage (Δ) in trunk diameter from beginning to end of trial (2004–2006). Values are means ± standard errors.

Variables	Year/Treatments	DR	SDI 0	SDI 120
Dry mass shoot $^{-1}$ (g)	2004	$59.0^{n.s.} \pm 5.06$	70.6 ± 3.03	71.3 ± 3.98
	2005	$57.7^{b} \pm 4.23$	$65.3^{ab} \pm 5.09$	$78.5^{a} \pm 5.14$
Dry wood shoot^{-1} (%)	2004	$46.0^{a} \pm 2.56$	$48.3^{a} \pm 2.40$	$35.3^{b} \pm 1.97$
	2005	$53.5^{a} \pm 2.01$	$50.9^{ab} \pm 1.55$	$47.9^{b} \pm 2.37$
Dry grapes shoot^{-1} (%)	2004	$54.0^{b} \pm 2.56$	$51.7^{b} \pm 2.40$	$64.7^{a} \pm 1.97$
	2005	$46.5^{b} \pm 2.01$	$49.1^{ab} \pm 1.55$	$52.1^{a} \pm 2.37$
Δ trunk diameter (%)	2004–2006	$29.46^{b} \pm 1.81$	$27.14^{ab} \pm 1.45$	$25.04^{a} \pm 1.76$

Within year, lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments according to Tukey's HSD test, n.s. = not significant.

Table 7
Balance Indices in Cabernet Sauvignon grapevines in 2004 and 2005 subjected to different irrigation systems DR, SDI 0 and SDI 120: total leaf area to yield ratio ($m^2\ kg^{-1}$), yield to wood wt ratio ($kg\ kg^{-1}$), water use efficiency at crop level WUE_y ($t\ ML^{-1}$), water use efficiency at plant level WUE_b ($t\ ML^{-1}$). Values are means ± standard errors.

Year	Treatment/Variable	Total leaf area yield ratio ($m^2\ kg^{-1}$)	Yield to wood wt ratio ($kg\ kg^{-1}$)	WUE_y[a] ($t\ ML^{-1}$)	WUE_b[b] ($t\ ML^{-1}$)
2004	DR	$2.31^{a} \pm 0.27$	$2.80^{b} \pm 0.19$	$5.20^{b} \pm 0.50$	$11.69^{n.s.} \pm 1.05$
	SDI 0	$1.77^{b} \pm 0.23$	$2.70^{b} \pm 0.18$	$6.44^{ab} \pm 0.29$	12.65 ± 0.87
	SDI 120	$1.16^{b} \pm 0.27$	$3.84^{a} \pm 0.26$	$8.12^{a} \pm 0.61$	12.04 ± 0.90
2005	DR	$3.33^{a} \pm 0.34$	$2.01^{b} \pm 0.21$	$5.50^{c} \pm 0.34$	$14.07^{b} \pm 1.00$
	SDI 0	$2.31^{b} \pm 0.31$	$2.27^{ab} \pm 0.24$	$7.26^{b} \pm 0.45$	$17.08^{a} \pm 0.75$
	SDI 120	$1.14^{c} \pm 0.22$	$2.73^{a} \pm 0.20$	$9.22^{a} \pm 0.38$	$17.53^{a} \pm 1.03$

Within year, lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments according to Tukey's HSD test, n.s. = not significant.

[a] Yield per ha/total water amount ($t\ ML^{-1}$).

[b] Fresh mass per ha/total water amount ($t\ ML^{-1}$).

Table 8
Indices between aerial biomass and root surface in Cabernet Sauvignon grapevines in 2004 and 2005 subjected to different irrigation systems DR, SDI 0 and SDI 120: yield to roots ratio ($kg\ m^{-2}$), wood mass to roots ratio ($kg\ m^{-2}$), yield plus wood mass to roots ratio ($kg\ m^{-2}$). Values are means ± standard errors.

Year	Treatment/Variable	Wood wt to roots ratio ($kg\ m^{-2}$)	Yield to roots ratio ($kg\ m^{-2}$)	Yield plus wood wt to roots ratio ($kg\ m^{-2}$)
2005	DR	$0.12^{c} \pm 0.01$	$0.25^{b} \pm 0.03$	$0.37^{b} \pm 0.05$
	SDI 0	$0.17^{b} \pm 0.02$	$0.38^{ab} \pm 0.05$	$0.55^{ab} \pm 0.08$
	SDI 120	$0.21^{a} \pm 0.01$	$0.57^{a} \pm 0.07$	$0.78^{a} \pm 0.07$

Within year, lowercase and different letters indicate statistically significant differences at $p < 0.05$ between treatments according to Tukey's HSD test, n.s. = not significant.

and surface drip irrigation systems, although a slightly higher yield was recorded in subsurface drip irrigation, due to a higher cluster weight, probably the lack of significant differences were due to rainfall (354 mm) during the growing season (Trigo-Córdoba et al., 2013). Furthermore, in cv. "Thompson Seedless" grapevine growing in India, subsurface irrigation produced a higher yield than surface drip irrigation (Sharma et al., 2005). Sharma and Upadhyay (2011) observed higher productive, vegetative and total soluble solid performances using a subsurface drip irrigation system receiving 25% less water than surface drip irrigation. Gaiotti (2010) on a four year old cv. "Merlot"/161-49 vineyard, grown on a loam-sandy soil in the DOC Piave Area, discovered that yield and berry weight were lower when using a subsurface drip irrigation located at 135 cm from the row compared to surface drip irrigation and subsurface drip irrigation placed at 40 cm from the row. In lemon trees, the use of a subsurface system with approximately 19% less water compared to surface irrigation increased water use efficiency without affecting yield and fruit growth (Robles et al., 2016); similar results were obtained in a cv. "Arbequina" organic olive orchard, with an increase of olive and oil yield (Martínez and Reca, 2014).

At harvest, the DR and SDI 0 treatments displayed a higher leaf area because of lower percentage of main and lateral leaf abscission after veraison which occurs frequently in semi-arid conditions (Di Lorenzo et al., 1992; Keller, 2005; Lovisolo et al., 2010; Romero et al., 2010; Merli et al., 2015). However, all irrigation systems showed the same vigour in terms of vegetative growth up to veraison, and similar wood weight at pruning.

Studies of vegetative performance among different irrigation systems, have shown contrasting results. For example, no effect on pruning weight per plant of cv. "Sultanina" (Myburgh, 2007b) and cv. "Godello" (Trigo-Córdoba et al., 2013) grapevine was observed when comparing surface and subsurface drip irrigation, while Gaiotti (2010), found a noticeable effect of irrigation method on shoot vigour in cv. "Merlot"; surface drip irrigation and subsurface irrigation systems located close to the trunk had a positive influence on leaf area and shoot growth compared to subsurface irrigation driplines located more distant from the trunk.

No difference in vegetative growth was shown when maintaining predawn water potential values between −0.2 and −0.4 MPa up to veraison, while maintaining predawn water potential values between −0.4 and −0.6 MPa after veraison, resulted natural defoliation, especially in the subsurface drip irrigation treatments. Leaf abscission in SDI 120 was probably caused by non-uniformity in root wetting and a lower presence of fine roots, which were unable to support the high atmospheric water demand during the day when combined with regulated deficit irrigation strategies. However, over the ripening period, fine roots located wet zone maintained a constant predawn leaf water potential. In subsurface irrigation only the terminal root portions, in contact with the wet soil area, are active in absorbing water while the roots nearest to the trunk, close to dry layers, are functionally inactive. We do not know whether SDI treatments after prolonged exposure to drying soil conditions produced a lower number of fine roots or were lost as occurs in partial rootzone drying (PRD) (Lovisolo et al., 2010).

Results obtained by researchers studying root apparatus (number, distribution and length) in different irrigation systems are also often contradictory, probably due to the different levels of water stress imposed in different experiment. In this study, surface drip irrigation showed a higher fine root contacts and length per dm^2, more presence of fine roots near the trunk (Bassoi et al., 2003), and a deeper root development, and growth following water movement in sandy soil. Gaiotti (2010) on cv. "Merlot" observed that in surface drip irrigation and subsurface drip irrigation with lines positioned closer to the vine row, there was higher root density but shallower development. On the contrary, Myburgh (2007b) found lower root density in the above-ground drip compared to subsurface drip irrigation and lower root density around the trickle lines at 30 cm and 45 cm depths. In mature almond, subsurface drip irrigation produced a greater horizontal distribution of fine roots in the soil profile than in a surface drip system and finer root density near the emitters. Moreover, root growth was deeper and root density was higher in subsurface drip irrigation under regulated deficit irrigation condition (Romero et al., 2004*)*. These root patterns were also discovered in some species where subsurface drip irrigation was applied (Phene et al., 1991; Ayars et al., 1999).

A lower leaf area/yield ratio at harvest in SDI 120 probably increased carbohydrate reserves translocation from the permanent structures to the reproductive organs (to support grape ripening), resulting in lower trunk growth (Candolfi-Vasconcelos et al., 1994). Reduction in trunk growth in subsurface irrigation systems was also found in lemon trees (Robles et al., 2016), but not in almond (Romero et al., 2004).

Grape quality largely depends on the sugar/acid balance at harvest. These parameters, are generally, dependent on the *terroir* (cultivar, soil, climate and vineyard management). In this study, the "Cabernet Sauvignon" must was characterized by low sugar and low acidity values. There is a clear vintage effect on yield and sugar accumulation, because of rainfall during the two years. Moreover, Zoldoske et al. (1998), in California using cv. "Sauvignon Blanc" on Freedom found contrasting results in yield, sugar, pH and titratable acidity from year to year when comparing subsurface versus surface drip irrigation system.

Differences in sugar levels between irrigation treatments in this study are consistent with differences in total leaf area/yield ratios, similar to results reported by Kliewer and Dokoozlian (2005). In surface drip irrigation, a higher sugar level was observed when total leaf area per shoot was higher (due also to a lower leaf fall during the ripening period) and productivity was lower.

Titratable acidity strongly contributes to juice stability, and is also a parameter commonly used as an indicator of quality. During the 2004 and 2005 seasons, higher titratable acidity was found in SDI 120, where higher yields per vine were observed. However, Myburgh (2007b) found that different subsurface irrigation treatments did not have a significant effect on sugar and acid content in the must compared to furrow irrigation or above-ground drip over three seasons.

Regulating grapevine water deficit is an efficient approach for managing the amount of secondary metabolites and improving wine quality (Kennedy et al., 2002; Castellarin et al., 2007). The SDI 120 irrigation treatment had a significantly higher level of anthocyanins expressed per berry, probably due to the larger berry size (Barbagallo et al., 2011; Pisciotta et al., 2013) and/or to differential root growth and architecture together with the associated differences in ABA synthesis, factors that were shown, to affect the metabolism of secondary compounds in PRD experiments by Stoll et al. (2000) and Jiang and Hartung (2008). However, there were no differences in anthocyanins expressed in $mgkg^{-1}$ of grapes among irrigation treatments (Gaiotti 2010).

In arid and semi-arid regions where a water resources for irrigation are scarce, improvement of water use efficiency (WUE) is needed through the optimization of the yield to water consumption ratio for vineyards (Chaves et al., 2010; Tomás et al., 2014; Medrano et al., 2015; Costa et al., 2016). This research manipulated irrigation schedule by introducing the subirrigation systems to reduce water supply. The WUE_y was modified by applying less water and having higher yield. The same results have been obtained in lemon crop, where the SDI system has improved the irrigation water use efficiency compared to a traditional DR system. In our research, 20% water savings were achieved with this new irrigation method. Subsurface drip irrigation (SDI) could influence water use, potential water losses, water uptake, and vine behaviour compared to drip and other irrigation methods (Sharma et al., 2005; Myburgh, 2007b; Gaiotti, 2010; Sharma and Upadhyay, 2011; Fandiño et al., 2012; Trigo-Córdoba et al., 2013; Cancela et al., 2015; Phogat et al., 2017).

5. Conclusions

The irrigation treatments influenced vegetative, reproductive, and qualitative parameters, root distribution and water use efficiency. Subsurface irrigation systems reduced water consumption, yielding higher grape production with 20% less water. All subirrigation treatments resulted in increased yield without a significant reduction in grape quality. Moreover, better results were found with inter-row water application rather than with inrow application. Placing the drip lines 120 cm away from the vine resulted in an increase in yield and carbon partitioning towards the reproductive organs.

One potential shortcoming of the SDI 120 irrigation strategy combined with regulated deficit irrigation, in sandy soil, is possible negative effects on the storage of reserves in permanent organs, considering higher leaf senescence, lower root presence, and lower trunk growth. These aspects deserve further investigation, and further studies may help to define the optimum parameters and conditions for successful adoption of the SDI 120 irrigation strategy.

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