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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

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ABSTRACT

Precision irrigation in grapevines could be achieved using physiologically based irrigation scheduling methods. This paper describes an investigation on the effects of three midday stem water potential (midday Ψ_S) thresholds, imposed from post-setting, over water use, vegetative growth, grape quality and yield of grapevines cv. Cabernet Sauvignon. An experiment was carried out on a vineyard located at the Isla de Maipo, Metropolitana Region, Chile, throughout the 2002/03, 2003/04 and 2004/05 growing seasons. Irrigation treatments consisted in reaching the following midday Ψ_S thresholds: −0.8 to −0.95 MPa (T1); −1.0 to −1.2 MPa (T2) and −1.25 to −1.4 MPa (T3) from post-setting to harvest. Results showed significant differences in grape quality components among treatments and seasons studied. In average, T3 produced smallest berry diameter (6% reduction compared to T1), high skin to pulp ratio (13% increment compared to T1) and significant increments in soluble solids and anthocyanins. Improvements in grape quality attributes were attributed to mild grapevine water stress due to significant reductions in water application (46% for T2 and 89% for T3 less in average, both compared to T1). This study found significant correlations between midday Ψ_S and berry quality components, no detrimental effects on yield by treatments were found in this study. This research proposes a suitable physiological index and thresholds to manage RDI and irrigation scheduling on grapevines to achieve high quality grapes on mild water stress conditions.

1. Introduction

High international competition and increasing internal produce offer in the Chilean winery industry have resulted in significant changes in productive strategies. The main change in the last 10 years has been the prioritization of high quality wines production over volume through on-farm management improvements such as new irrigation strategies. Accurate control of water deficits, through deficit irrigation or other cultural practices, is necessary to obtain high quality grapes for wine production (Ojeda et al., 2002; Coombe and Iland, 2005; Pellegrino et al., 2005). Several studies have shown that changes in grapevine water status, at critical phenological stages, have a direct effect on grape composition and quality attributes by influencing vegetative growth, yield, canopy microclimate, and fruit metabolism (Dry and Loveys, 1998; Van Leeuwen and Seguin, 1994; Pellegrino et al., 2005; Ezzhaouani et al., 2007). Thus, the implementation of regulated deficit irrigation (RDI) can result in substantial improvements on fruit quality through decreasing yield and berry size (Peterlunger et al., 2002; Ojeda et al., 2002; Pellegrino et al., 2005). Specifically, it has been found that RDI has a positive effect over synthesis and concentration of phenolic compounds, soluble solids, and anthocyanins (Ginestar et al., 1998b; Ojeda et al., 2002; Van Leeuwen et al., 2004). Moreover, Trégoat et al. (2002) deals with the positive effect of water deficit in un-irrigated vines. These improvements are directly related to wine quality components, such as colour, flavour and wine aroma due to an increment of skin to pulp ratio in berries (Williams and Matthews, 1990; Koundouras et al., 2006). Furthermore, high soluble solids concentration can be found on vines under RDI (Koundouras et al., 1999). However, Goodwin and Jerie (1992) showed that vines under severe RDI presented grapes with lower soluble solids concentration. Furthermore, Peterlunger et al. (2002) did not find significant

Abbreviations: Midday Ψ_S, midday stem water potential; RDI, regulated deficit irrigation; Ψ_L, leaf water potential; Ψ_S, stem water potential; Ψ_{PD}, pre-dawn leaf water potential; SP_ratio, skin to pulp ratio; E.E. anthocyanins, easily extractable anthocyanins; S_solid, soluble solid.

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differences in sugar accumulation on berries of grapevines under RDI. These apparent contradictory results show that the success of applying RDI to achieve higher quality grapes may be related to the accuracy of vine water status monitoring to regulate and manage positive physiological changes imposed to the vines by deficit irrigation.

Depending on the accuracy of the method used, vine water status monitoring can lead to the development of a relevant tool for irrigation scheduling, which could enable grape growers to optimally manage vegetative and fruit growth in grapevines using RDI. Therefore, an accurate method to obtain vine water status measurements should be one which responds quickly and accurately to: (i) vine water restriction, (ii) soil water availability, (iii) soil hydraulic conductivity and (iv) the capacity of the vine to transport water from the soil to the atmosphere (Choné et al., 2000, 2001a,b). Thus, manipulation of berry quality and vine vigour can be achieved using an irrigation scheduling technique, which considers the soil–plant–atmosphere interactions. Many authors have proposed the use of the pressure chamber method (Scholander et al., 1965) as an excellent tool to measure vine water status under irrigated and non-irrigated conditions (Naor et al., 2001; Ojeda et al., 2002; Girona et al., 2006; Sibille et al., 2007). Vine water status can be assessed using different pressure chamber approaches, such as, leaf water potential (Ψ_L), stem water potential (Ψ_S), and pre-dawn leaf water potential (Ψ_{PD}) (Choné et al., 2000, 2001b; Ojeda et al., 2002; Girona et al., 2006; Sibille et al., 2007). These methods are widely used and constitute reference measurements of vine water status, from low to very high levels of water restriction on vine (Ojeda et al., 2002; Tisseyre et al., 2005; Acevedo-Opazo et al., 2008). However, midday Ψ_S has been proposed as a very sensitive physiological indicator of whole plant water status for fruit trees and grapevines under irrigation (Stern et al., 1998; Naor et al., 2001; Mc Cutchan and Shackel, 1992; Cifre et al., 2005; Shackel, 2007). The measuring procedure for Ψ_S involves covering a leaf with an aluminium foil bag coated with plastic to stop leaf transpiration. Midday Ψ_S also corresponds to measurements of this parameter at the time of the day when the evaporative demand by the atmosphere is at its maximum (Mullins et al., 1996). When transpiration of the bagged leaf is close to zero, Ψ_L equilibrates with Ψ_S. Therefore, the value of water potential measured in the chamber represents midday Ψ_S. Choné et al. (2001b) showed that Ψ_S is a sensitive physiological indicator, under irrigation conditions, which represents the ability of vines to transport water from the soil to the atmosphere. The success of midday Ψ_S as plant water status indicator in grapevines lays in the low variability that this parameter presents compared to Ψ_L, since Ψ_S represents the water status of the whole vine, rather than of single leaves in the canopy (Ψ_L).

As a general guideline, grapevines without any water stress would present midday Ψ_S values above to -1.0 MPa, moderate water restriction can be found at values from -1.0 to -1.2 MPa and values from -1.2 to -1.5 MPa corresponds to severe water stress (Sibille et al., 2007; Cifre et al., 2005; Ferreyra et al., 2003; Williams and Araujo, 2002; Trégoat et al., 2002; Lampinen et al., 2001). The link between midday Ψ_S and berry quality attributes was shown by Trégoat et al. (2002), who found a strong correlation between this parameter and anthocyanins, phenols and malic acid content in berries. These authors also found good correlations between midday Ψ_S and grape berry weight and yield.

In this paper, midday Ψ_S is presented as a potentially accurate indicator of plant water status diagnosis to achieve RDI in grapevines (cv. Cabernet Sauvignon). Therefore, the objective of this research was to determine the effect of different midday Ψ_S thresholds over water consumption, vegetative growth, grapes quality and yield of Cabernet Sauvignon grapevines located in the Isla de Maipo, Metropolitan region of Chile over three growing seasons.

2. Materials and methods

2.1. Experimental site

An experimental site of 3250 m^2, was established in a 9-year-old commercial grapevine orchard (cv. Cabernet Sauvignon) located at the Isla de Maipo, Metropolitana Region (33°46′16″ LS; 70°55′34″ LW; 304 m.a.s.l.), Chile. The vines were irrigated by surface drip irrigation (one dripper per vine at 3.6 L h^{-1}) and planted at 2.5 m between rows and 1.3 m between plants. The training system used was vertical shoot-positioned with rows oriented NW–SE and pruned leaving 20 stems per shoot per linear meter. Vineyard canopy management, such as trimming or toping were performed early in the season at the experimental plot. This practice is usually performed in commercial vineyards from the region. The historical average yield for this site is approximately of 9 tons ha^{-1}. The growing seasons monitored were 2002/03, 2003/04 and 2004/05. The climate for the area is classified as a warm semi-arid Mediterranean with sea influence. The maximum and minimum average temperatures in summer are 29 and 9.5 °C, respectively. Average yearly accumulated rain is 419 mm with 997 mm of water deficit and a dry period of 8 months. The soil type belongs to the Maipo series (Mollisol), with deep loamy texture. To determine the physical, hydrological and root depth characteristics of the soil and orchard, soil samples were extracted randomly from two excavation pits in representative areas from the experimental site. Total depth of root zone corresponded to 3.5 m; bulk density = 1.41 g cm^{-3}; field capacity = 25% vol. (875 mm); wilting point = 13% vol. (455 mm); and total soil water holding capacity of 420 mm.

2.2. Seasonal dryness characterization

Experiments were carried out during 3 different years with different climatic conditions (Table 1). The dryness index (DI, mm) proposed by Tonietto and Carbonneau (2004) (Eq. (1)), was used to characterise seasonal potential soil water balance for the 6-month period from October 1st to March 30th. The seasonal DI was calculated to identify whether there were different levels of soil water stress placed on the vines in different seasons. A season with a DI value <50 is considered to impose soil moisture stress to vines. Therefore, the lower the DI value the higher the stress.

$$\mathrm{DI} = \sum_{\mathrm{Mi}}^{\mathrm{Mf}} W_o + P - T_v - E_s \tag{1}$$

where W_o is the initial useful soil water reserve available to roots (mm), P is the monthly precipitation (mm), T_v is the potential monthly transpiration of the vineyard (mm) and E_s is the monthly direct evaporation from the soil (mm). Climates are considered to be humid (DI > 150 mm), sub-humid (150 > DI > 50 mm), moderately dry (50 > DI > −100 mm) or very dry (DI < −100 mm).

2.3. Grapevine water use

Vineyard evapotranspiration (ET_v) was estimated daily using a class A evaporation pan. Reference evapotranspiration (ET_0) was

Table 1
Summary of the main climatic parameters characterizing growing conditions during the 3 years that experiment was carried out.

Seasons	Pp (mm)	ET_0 (mm)	DI (mm)
2002–2003	350	676	−28
2003–2004	283	692	−42
2004–2005	247	715	−79

Pp, cumulative precipitation; ET_0, cumulative reference evapotranspiration; DI, resulting dryness index.

obtained using the pan evaporation data (ET_p) corrected by a pan coefficient (Kp = 0.75) according to wind velocity and relative humidity of the study period (Ben-Asher et al., 2006):

$$ET_v = ET_p \times Kp \times Kc \tag{2}$$

where ET_v and ET_p are in mm d^{-1}.

Suitable crop coefficients (Kc) and Eq. (1) were used to calculate crop evapotranspiration (ET_c). The Kc values used were: 0.15, 0.35, 0.55, 0.30 and 0.20 for November, December, January, February and March, respectively. These Kc values are commonly used in the Isla de Maipo, Metropolitan region to obtain quality wines for the cv. Cabernet Sauvignon.

Air temperature, wind velocity and rain were measured using an automatic meteorological station (Davis Vantage Pro, Davis Ca., USA), which was installed, close to the evaporation pan, over a reference grass area. Effective rain was calculated according to methodology proposed by Goodwin (1995). Irrigation timing was calculated using the following expression:

$$IT = \frac{ET_v \times Ps \times AU}{Ne \times Ea \times q} \tag{3}$$

where IT = irrigation timing (h), Ps = fraction of shade in relation to the unit (1), AU = area designated to the crop (m^2), Ne = number of emitters per plant, Ea = application efficiency of irrigation system (0.85) and q = emitter flow (L h^{-1}).

2.4. Grapevine physiological and grape quality variables

Midday Ψ_S was measured using a pressure bomb (PMS Instruments Co., Model 600, Corvallis, Oregon, USA) (Scholander et al., 1965). Five mature, healthy and fully expanded leaves were selected from five vines from each replicate. The leaves were selected from the middle of the canopy at the sunny side and they were bagged in plastic bags coated with aluminium foil (to avoid overheating) for at least 2 h prior measurements. A maximum of 30 s elapsed between cutting the leaves and the measurements. Measurements were conducted in one date for each key phenological stage (post-setting, veraison, post-veraison and pre-harvest).

Shoot length, distance between stems and number of stems per shoot were measured from five vines per replicate with similar trunk diameter at 60 cm of high from the soil. These measurements were also performed fortnightly from post-setting to pre-veraison (late January). Pruning weight was obtained between June and July for each season from five vines per replicate. At harvest, different parameters were also measured to characterise yield per plant, maturity and berry quality. These measurements were based on cluster samples of five plants per replicate for each treatment. Soluble solid concentration (using a thermo-compensated refractometer), total acidity (g L^{-1} of sulphuric acid) and pH (potentiometer) were measured at berry maturity. Yield components were also evaluated, such as: number of clusters per vines, clusters weight, number of berries per cluster and fruit weight per vine. To evaluate berry composition, measurements of skin to pulp ratio and total and easily extractable anthocyanins were assessed at harvest using the methodology proposed by Iland et al. (2000).

2.5. Irrigation treatments

The experimental design consisted in three irrigation treatments with three replicates per treatment, which were imposed from post-setting (late November for all seasons). The treatments consisted in supply irrigation to vines to maintain midday Ψ_S values between −0.8 and −0.95 MPa for T1; −1.0 to −1.2 MPa for T2 and from −1.25 to −1.4 MPa for T3. Treatments and replicates were randomly distributed in the experimental area. Each replicate consisted in a row of approximately 100 m long containing 77 vines. Five representative vines, from the middle of each replicate, were selected for midday Ψ_S measurements.

2.6. Data analysis

Principal component analysis (PCA) was used to obtain a hierarchy of the variables analysed, to find patterns in the data and to classify any combination of variables that could explain effect of irrigation treatments on growth and berry quality variables for the three seasons. Therefore, the data set used for the PCA analysis contained the three growing seasons (2002/03, 2003/04, 2004/05) and irrigation treatments (T1, T2, T3), which were analysed on four growth variables: (i) berry number per cluster (B_number), (ii) berry weight (B_weight), (iii) shoot length (S_length) and (iv) pruning weight (P_weight); and three berry quality variables: (i) skin to pulp ratio (SP_ratio), (ii) easily extractable anthocyanins (E.E._anthocyanins) and (iii) soluble solids (S_solids). The PCA analysis was made using a script written in MATLAB® 7.0 (The Mathworks Inc., Natick, MA, USA). The variables measured were also evaluated statistically using a two-way ANOVA test (Statgraphics 5.1. Statpoint Inc., Virginia, USA). When differences were statistically significant, a multiple Duncan comparison was used to separate means with a 95% confidence level. The relationships between midday Ψ_S and berry quality components (skin to pulp ratio, anthocyanins E.E. and total anthocyanins) were analysed using linear regression analyses. Variables with a significant relationship were evaluated using the Pearson's correlation coefficient threshold value at $p < 0.05$ of 0.67, which corresponds to seven degrees of freedom.

3. Results and discussion

3.1. Vine water consumption

Table 1 shows results of DI calculated for each of the three experimental seasons. The 2004/05 season presented the lowest DI (DI = −79 mm), which is close to very dry climate. The 2002/03 and 2003/04 seasons presented DI corresponding to moderately dry climate. These results show that moderate to high water restrictions were experienced during the 3 years of the experiments. According to these results, in 2004–2005 and to a lesser extent in 2003–2004, high vine water restriction was expected at the end of the season (veraison–harvest).

During the 2002/03 growing season, total rain corresponded to 255 m^3 ha^{-1} (25.5 mm), which was distributed as follows: budburst–setting (57.6%), setting–veraison (11.8%) and veraison–harvest (30.6%). The rain registered in the second (2003/04) and third (2004/05) growing season corresponded to 205 and 178 m^3 ha^{-1}, respectively, which was concentrated during the budburst–setting period, for both seasons (Table 2). Maximum atmospheric demand (ET_0) was registered between December and January for all the growing seasons studied. Maximum daily ET_0 values were of 6.5 mm d^{-1} in average, with accumulated values of 676.1, 692.4 and 714.9 mm for the 2002/03, 2003/04 and 2004/05 growing seasons, respectively (Table 2). A gradual increment in dryness (from season 2002/03 to 2004/05) was observed when comparing the evaporative demand and rain conditions registered. Therefore, season three (2004–2005) can be considered the driest season compared to the previous two, since it registered higher ET_0 (7149 m^3 ha^{-1}) and lowest effective rain (168 m^3 ha^{-1}). According to these results, there was a gradual decrease in water availability from the soil to the plants from season one to three. Furthermore, decreasing winter rain was also responsible for low water recharge of the soil profile in winter (data not shown).

Table 2
Effective rain Ef_{rain} ($m^3\,ha^{-1}$), reference evapotranspiration ET_0 ($m^3\,ha^{-1}$), average maximum T_{max} (°C) and minimum T_{min} temperatures (°C) over the main grapevine phenological stages for the three growing seasons studied on cv. Cabernet Sauvignon.

Season	Budburst–setting	Setting–veraison	Veraison–harvest	Total
2002–2003				
Ef_{rain} ($m^3\,ha^{-1}$)	147	30	78	255
ET_0 ($m^3\,ha^{-1}$)	1602	2537	2622	6761
T_{max} (°C)	23.8	30.4	29.7	–
T_{min} (°C)	12.3	13.4	12.8	–
2003–2004				
Ef_{rain} ($m^3\,ha^{-1}$)	205	0	0	205
ET_0 ($m^3\,ha^{-1}$)	1660	2544	2720	6924
T_{max} (°C)	24.5	30.8	29.0	–
T_{min} (°C)	10.8	11.5	11.7	–
2004–2005				
Ef_{rain} ($m^3\,ha^{-1}$)	178	0	0	178
ET_0 ($m^3\,ha^{-1}$)	1673	2683	2793	7149
T_{max} (°C)	23.1	31.2	29.6	–
T_{min} (°C)	11.0	10.8	10.9	–

Effective rain (mm) = (pluviometric precipitation − 10) × 0.75 (Goodwin, 1995).

Due to soil conditions of the experimental site (deep loamy soil with an effective root zone of 350 cm and a high soil water holding capacity of 420 mm), water was not a limiting factor for vegetative growth on the three seasons studied. Furthermore, since the maximum evaporative demand was achieved later in the summer (end of January), water restriction values (<−1.0 MPa) were reached only from veraison for T2 and T3 in the first and third season and from post-veraison for T2 and T3 in the second season.

The number of irrigations applied were 23, 19 and 20 for T1; 13, 9 and 10 for T2 and 1, 3 and 4 for T3 during the seasons 2002/03, 2003/04 and 2004/05, respectively. Total maximum and minimum water applied corresponded to 2570 $m^3\,ha^{-1}$ for T1 and 111 $m^3\,ha^{-1}$ for T3 (season 2002/03). In the second season (2003–2004), irrigation water applied was less in T1 (2080 $m^3\,ha^{-1}$) and increased for T3 (350 $m^3\,ha^{-1}$) compared to the first season. In the third season (2004/05), water applied corresponded to 2185 $m^3\,ha^{-1}$ for T1 and 418 $m^3\,ha^{-1}$ for T3 (Table 3). Water volumes applied in T1 were similar to those applied by Ginestar et al. (1998a,b), which were 2000 $m^3\,ha^{-1}$ for cv. Shiraz in South Australia. However, water

Table 3
Water application ($m^3\,ha^{-1}$) from setting to veraison (S–V) and veraison to harvest (V–H) (cv. Cabernet Sauvignon).

	Season 2002–2003			Season 2003–2004			Season 2004–2005		
Treatment	S–V	V–H	Total	S–V	V–H	Total	S–V	V–H	Total
T1	111	2459	2570	620	1462	2082	598	1587	2185
T2	111	1351	1462	265	798	1063	314	803	1117
T3	111	0	111	0	355	355	0	418	418

volumes differed considerably from those applied by Nadal and Arola (1995), which were of 4500 $m^3\,ha^{-1}$ for Cabernet Sauvignon in Spain. In Chile, Ferreyra et al. (2002, 2003), applied 4400 and 4700 $m^3\,ha^{-1}$ for semi-arid conditions in Pirque, for non-stressed treatments, respectively. These differences in total water application can be related to four main factors: (i) cultivar, (ii) management (vegetative growth, fruit load and productive objective), (iii) soil water holding capacity, (iv) variation in local climatic conditions and (v) method of used to estimate vine water requirement.

3.2. Vine water status

The lower midday Ψ_S values were achieved by T2 and T3 with averages below −1.0 MPa from veraison, for all studied seasons (Table 4). On the contrary, T1 maintained midday Ψ_S values above −1.0 MPa for all seasons studied. These results coincide to those obtained by Choné et al. (2001b), Williams and Araujo (2002), Ferreyra et al. (2003), Cifre et al. (2005) and Sibille et al. (2007) who found that midday Ψ_S values above to −1.0 MPa correspond to grapevines without any water restriction.

The timing of water restriction during grapevine development is critical to the success of RDI. Water restriction applied in the following stages can/cannot show a positive effect: (i) during canopy development, leads to insufficient leaf area after veraison, reducing the rate of sugar synthesis and causing sun damage to berries (Weeks et al., 1984); (ii) during flowering, reduces yield due to abscission and desiccation of flowers (Hardie and Considine, 1976); (iii) after flowering, there is no negative impact on cell division but in pericarp mean cell volume (pulp and skin) for young berries (Ojeda et al., 2001); (iv) between setting and veraison, significantly reduces vigour but yield is reduced partially (Williams and Matthews, 1990; Goodwin and Macrae, 1990)

Table 4
Midday stem water potential (Ψ_s) in MPa, measured at different grapevine phenological stages and corresponding standard deviations (±SD) for the three seasons (cv. Cabernet Sauvignon).

Treatments	Post-setting (MPa)	Veraison (MPa)	Post-veraison (MPa)	Pre-harvest (MPa)
Season 2002–2003				
T1	−0.72 ± 0.12	−0.86 ± 0.16b	−0.70 ± 0.13 b	−0.66 ± 0.14 c
T2	−0.70 ± 0.14	−1.08 ± 0.15 a	−1.02 ± 0.18a	−0.91 ± 0.15 b
T3	−0.70 ± 0.15	−1.07 ± 0.18 a	−1.04 ± 0.18a	−1.15 ± 0.19 a
Significance	n.s.	*	*	*
Season 2003–2004				
T1	−0.74 ± 0.15	−0.58 ± 0.16c	−0.67 ± 0.13b	−0.72 ± 0.14c
T2	−0.70 ± 0.13	−0.79 ± 0.17b	−0.97 ± 0.12a	−1.01 ± 0.13b
T3	−0.73 ± 0.16	−0.92 ± 0.20a	−1.00 ± 0.18a	−1.18 ± 0.21a
Significance	n.s.	*	*	*
Season 2004–2005				
T1	−0.66 ± 0.14	−0.97 ± 0.10c	−1.09 ± 0.06b	−1.07 ± 0.08b
T2	−0.64 ± 0.15	−1.13 ± 0.16b	−1.22 ± 0.13a	−1.27 ± 0.12a
T3	−0.66 ± 0.21	−1.19 ± 0.19a	−1.27 ± 0.15a	−1.31 ± 0.18a
Significance	n.s.	*	*	*

Values followed by the same letter are not significantly different (Duncan $p \leq 0.05$).
n.s.: non-significant.
* Significant ($p \leq 0.5$).

and finally (v) between veraison and harvest, there are no significant effects on yield (Williams and Matthews, 1990; Goodwin and Macrae, 1990).

3.3. PCA analysis

The amount of variation in the data that can be explained by different spread factors (principal components) can be expressed as follows: components 1 and 2 represented 75% and 14% of the total variation in the data set, respectively. Therefore, both components accounted for 89% of the total variability in the data. There were clear differences between treatments and seasons, which can be visualized in the case score plot presented in Fig. 1a. Three diagonal clusters are easily identifiable, which corresponded to treatments and seasons. A variable score plot is presented in Fig. 1b, which shows the variables that contributed to the spread along component 1 and component 2. Component 1 was negatively correlated with B_number, B_weight, S_length and P_weight. On the contrary, component 1 was positively correlated with SP_ratio, E.E._anthocyanins and S_solids. The later variable constituted a smaller percentage in the component 1. Variables, which were favoured by high water availability, were positioned on the left part of the spread plot. Variables that were positively correlated to mild water stress were positioned on the right side (Fig. 1b). Component 1 can be related to plant water status and its effects over plant vegetative expression, yield components and berry quality variables, underlying the relevance of irrigation management practices, such as RDI, on a vineyard under irrigated conditions. Component 2 was correlated with C_number and to a lesser extent with S_solids. C_number showed differences among seasons in the component 2 and S_solubles showed differences among treatments. The third season and T3 were the period and treatment of greater water restriction. On the other hand, variables related to yield showed a negative linear relationship with plant water status.

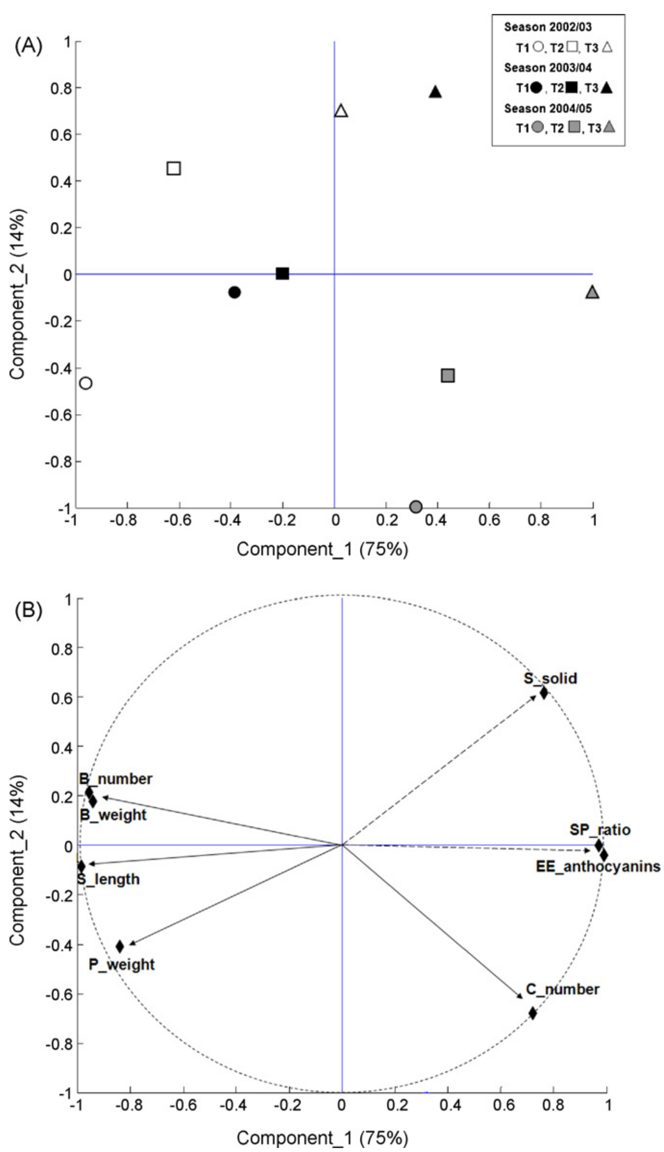

Fig. 1. PCA analysis considering all the data set from the 2002/03, 2003/04 and 2004/05 growing seasons for cv. Cabernet Sauvignon. A case score plot is presented in 1a, each point of the PCA represents the three irrigation treatments (T1, T2, T3) for the three growing seasons studied. A variable score plot is shown in 1b considering all variables measured. Solid lines characterise vegetative expression and yield components, dashed lines corresponds to berry quality variables. Nomenclature used: B_number, berry number per cluster; B_weight, berry weight; S_length, shoot length; P_weight, pruning weight; SP_ratio, skin to pulp ratio; E.E._anthocyanins, easily extractable anthocyanins; S_solids, soluble solids.

The vertical separation of treatments and seasons found in Fig. 1a can be explained by: (i) water stress levels imposed by treatments; (ii) increment in dryness from season to season and (iii) through the variables C_number, B_number and B_weight, since C_number is strongly influenced by the fruit load adjustment practise. The later is a common practice on vineyard management for the studied area to obtain quality grapes and consists in adjusting fruit load before harvest; therefore, eliminating excess clusters to reach the historical vineyard yield (9 tons ha^{-1}). Because of this, C_number has a greater representation on component 2 compared to component 1. When considering all seasons, T3 was the treatment that achieved higher values in berry quality components (Fig. 1a). Specifically, in the third season, T3 achieved higher anthocyanins and SP_ratio compared to the previous two seasons (Fig. 2a and b).

3.4. Vegetative growth and yield

The majority of the vegetative growth variables did not present significant differences among treatments nor within seasons (Table 5). Shoot length reached average values of 147 cm, number of stems was 25, the internode length was 5.9 cm and the pruning weight corresponded to 1.2 kg per plant. These results show that water restriction imposed were not enough to affect vine vegetative expression. Furthermore, no statistically significant differences were found in total yield among treatments, which reached an average of 9, 8 and 8 tons ha^{-1} for the 2002/03, 2003/04 and 2004/05 season, respectively (Table 6) after fruit load management. Yields achieved were consistent with those achieved historically in the area. The only significant difference in yield components was found in the number of berries per bunch during the first season (Table 6). In this case, T3 reached 112 berries in average compared to 134 for T1. These results were not observed in the other two seasons, since there was not significant differences in plant water status between budburst and post-setting; therefore, it was expected that flower induction and berry number per bunch would not be affected for the next seasons (2003/04 and 2004/05).

We hypothesize that moderately dry climate, which characterised the three seasons studied, (Table 1), played an important role in maintaining a balance between the level of water restriction imposed to the plants (T2 and T3) and the atmospheric demand for water. Frequently, under RDI, plant water status is also reduced due to a combined effect of high atmospheric demand and soil water deficit. Therefore, management problems arise when plants are under RDI in zones with high atmospheric demand in summer. In this scenario, high vine water restriction induces severe water

Table 5
Vegetative growth of cv. Cabernet Sauvignon vineyard (Isla de Maipo, Chile).

Treatments	Shoot length (cm)	Nodes number	Internode length (cm)	Pruning weight (g plant^{-1})
Season 2002–2003				
T1	156.3	26.0	6.0	1310
T2	154.3	27.1	5.7	1297
T3	136.0	23.7	5.7	1206
Significance	n.s.	n.s.	n.s.	n.s.
CV (%)	18.4	17.2	9.9	26.6
Season 2003–2004				
T1	149.0	24.0	6.2	1291
T2	151.0	25.0	6.0	1302
T3	139.0	24.0	5.8	1198
Significance	n.s.	n.s.	n.s.	n.s.
CV (%)	20.3	18.6	10.3	30.1
Season 2004–2005				
T1	139.0	23.0	6.0	1278
T2	136.0	23.0	5.9	1261
T3	128.0	22.0	5.8	1172
Significance	n.s.	n.s.	n.s.	n.s.
CV (%)	19.2	16.8	10.1	24.4

Values followed by the same letter are not significantly different (Duncan $p \leq 0.05$).
n.s.: non-significant.
CV: coefficient of variation (%).
Significant ($p \leq 0.5$).

restriction, which could compromise yield (Tardieu and Simonneau, 1998; Wilkinson and Davies, 2002). Although water is saved using RDI, the main objective in the implementation of this technique is the manipulation of grapevine physiology to increase quality of grapes and wine (Williams and Matthews, 1990; Esteban et al., 2001).

3.5. Grape quality

The quality of wine can be associated with berry size, sugar accumulation, total acidity and colour (tannin and anthocyanin content for red varieties) (Kliewer and Freeman, 1983). According to the PCA analysis, the variables most affected by the water

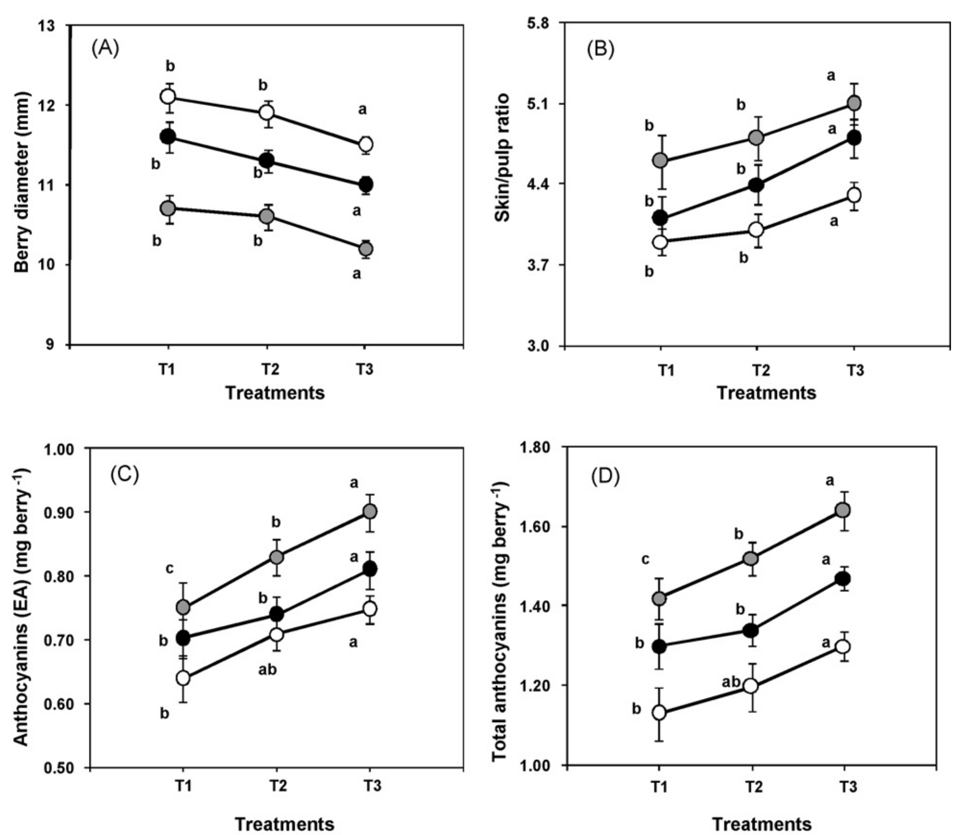

Fig. 2. Berry quality analysis expressed as berry diameter (A), skin to pulp ratio (B), E.E. anthocyanins (C) and total anthocyanins (D) for seasons 2002/03 (○), 2003/2004 (●) and 2004/05 (●). Values followed by the same letter are not significantly different (Duncan $p \leq 0.05$).

Table 6
Seasonal yield components for cv. Cabernet Sauvignon under three irrigation treatments.

Treatments	Bunches (No. plant^{-1})	Bunch weight (g)	Number of berries per bunch	Berry weight (g)	Yield (g plant^{-1})
Season 2002–2003					
T1	23.0	141.3	134	1.05	3250
T2	20.5	133.2	128	1.04	2731
T3	22.4	120.1	112	1.07	2892
Significance	n.s.	n.s.	*	n.s.	n.s.
CV (%)	29.3	25.1	22.0	19.0	42.3
Season 2003–2004					
T1	23	120.0	124	0.96	2783
T2	25	111.9	125	0.90	2823
T3	22	108.4	118	0.92	2385
Significance	n.s.	n.s.	n.s.	n.s.	n.s.
CV (%)	28.2	22.3	24.3	20.3	36.0
Season 2004–2005					
T1	32	106.5	99.3	1.07	3408
T2	29	108.1	107.0	1.01	3135
T3	31	99.0	97.1	1.01	3070
Significance	n.s.	n.s.	n.s.	n.s.	n.s.
CV (%)	30.5	24.5	27.0	23.4	37.2

Values followed by the same letter are not significantly different (Duncan $p \leq 0.05$).
n.s.: non-significant; CV: coefficient of variation (%).
* Significant ($p \leq 0.5$).

restriction treatments were: berry diameter, SP_ratio and anthocyanins. Berry size is an important factor to achieve quality wines, since it is a determinant factor in the maceration processes for red wines (Hepner et al., 1985), such as Cabernet Sauvignon. A smaller berry size (high surface/volume relationship or skin to pulp ratio) can be achieved using RDI (Williams and Matthews, 1990), which concentrate colour and flavour components, which are passed on to the wine (Matthews et al., 1990; Spiora and Gutiérrez, 1998). In this study, berry maturity, analysed at harvest, showed significant differences among treatments in soluble solids for T2 and T3 compared to T1 for the three seasons studied (Table 7). No differences were found for pH and total acidity; however, values reached were within the optimal range at harvest in all seasons studied and for all treatments (Coombe and Dry, 2002). Differences in soluble solids can be attributed to mild water stress imposed by T2 and T3 (Ψ_S values below −1.0 MPa). These results are in accordance to those obtained by Trégoat et al. (2002) and Ojeda et al. (2002), who found higher soluble solids concentration in berries of plants under moderate water restriction. Furthermore, Matthews et al. (1990) showed that soluble solids were greater in early deficit treatment (pre-veraison water restriction) than those in the late deficit treatment on cv. Cabernet Franc. In the third season, all treatments reached high soluble solids (above 24 °Brix), probably due to higher dryness presented at that particular season, which helped to enhance treatment effects.

Significant differences among treatments for berry diameter, skin to pulp ratio and E.E. and total anthocyanins for three seasons can be seen in Fig. 2. The highest berry diameter was achieved in T1 and T2, which were in average 12.0, 11.5 and 10.7 mm for the first, second and third seasons, respectively, with no statistical differences between T1 and T2 (Fig. 2a). These results are in contrast to T3, which showed the smallest berry diameter values in all the seasons studied. The opposite effect was observed for the skin to pulp ratio, where T1 and T2 showed the lowest averaged values with no statistical differences between treatments (Fig. 2b). The highest skin to pulp ratio values were found in T3 in the three seasons studied. These results were similar to those of Ginestar et al. (1998b), who found significant differences in skin to pulp ratio of berries for treatments with and without irrigation, respectively. Easily extractable anthocyanins were in average 0.75, 0.81 and 0.90 mg berry^{-1} for T3 in the first, second and third seasons, respectively (Fig. 2c). These results were also similar to those obtained by Ginestar et al. (1998b), Choné et al. (2001a) and Ojeda et al. (2002), who found higher anthocyanins concentrations in berries of plants under water restriction. This effect can be associated to the increment in the skin to pulp ratio of treatments with less irrigation (T3). A greater skin proportion favours the extraction of total anthocyanins and easily extractable anthocyanins (Ginestar et al., 1998b). Furthermore, Ginestar et al. (1998b) showed that anthocyanins content (total and E.E.) increased between 15% and 30% with water deficit applied in pre-veraison and post-veraison, respectively compared with control treatments. In this study, T3 increased in average the E.E. anthocyanins in 17.6% and 9.2% and total anthocyanins in 14.5% and 5.5% compared to T1 and T2, respectively for the three seasons studied (Fig. 2d). Furthermore, significant negative correlation ($p < 0.01$) were

Table 7
Seasonal grape maturity components at harvest for cv. Cabernet Sauvignon under three irrigation treatments.

Treatments	Soluble solids (°Brix)	pH	Total acidity (g/L)
Season 2002–2003			
T1	23.0b	3.6	2.5
T2	24.3a	3.6	2.9
T3	24.5a	3.6	2.7
Significance	*	n.s.	n.s.
CV (%)	3.5	1.8	11.7
Season 2003–2004			
T1	23.9b	3.6	3.1
T2	24.5a	3.7	2.9
T3	25.0a	3.6	2.9
Significance	*	n.s.	n.s.
CV (%)	4.8	3.2	2.9
Season 2004–2005			
T1	24.0b	3.6	2.9
T2	24.6a	3.5	2.8
T3	24.9a	3.5	2.7
Significance	*	n.s.	n.s.
CV (%)	1.5	1.8	2.2

Values followed by the same letter are not significantly different (Duncan $p \leq 0.05$).
n.s.: non-significant. CV: coefficient of variation.
* Significant ($p \leq 0.5$).

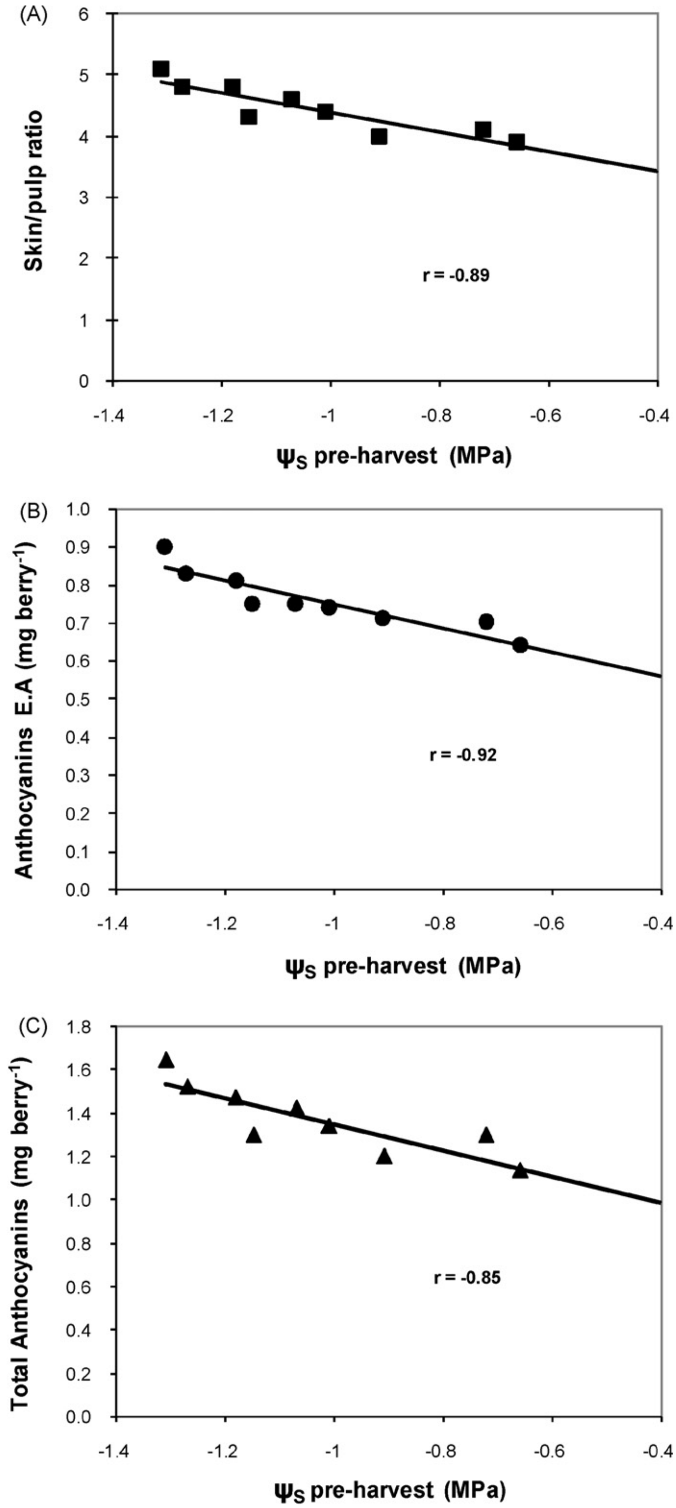

Fig. 3. Linear relationships between midday stem water potential (ψ_S) in MPa, measured at pre-harvest and berry quality analysis expressed as skin to pulp ratio (A: ■), E.E. anthocyanins (B: ●) and total anthocyanins (C: ▲) measured at harvest, on Cabernet Sauvignon.

found at pre-harvest between midday Ψ_S and berry quality components, such as skin to pulp ratio ($r = -0.89$), E.E. anthocyanins ($r = -0.92$) and total anthocyanins ($r = -0.85$) (Fig. 3). These results are in accordance to those found by Trégoat et al. (2002). From the correlation analysis between midday Ψ_S and berry quality components at harvest, it can be inferred that irrigation treatments affected considerably berry diameter (6% reduction in average) and skin to pulp ratio (13% increment) rather than affecting significantly the synthesis of these quality components. Therefore, berry size change is the most likely factor affecting anthocyanins content in berries at harvest.

Finally, better results, for berry quality components, were obtained in the treatment with lower water application (T3) during the three seasons. These results show that in dry-farming conditions (Trégoat et al., 2002; Choné et al., 2001a), for the specific soils of the study, it is expected a better grape quality, even higher to the one obtained for T3 in this study,

4. Conclusions

Using midday ψ_S as a vine physiological indicator, irrigation scheduling can be managed in a precise manner, since irrigation criteria is based on vine water demand rather than relaying on weather and/or soil moisture measurements. The particularities of the site studied in this paper, specifically root depth, helped to point out the pitfalls in attempting schedule irrigation using soil moisture or weather/physically based methodologies, which do not consider the plant in the assessment. Soil moisture monitoring has been an unpractical and uneconomical way to do irrigation scheduling in this area (Isla de Maipo), since root depth can reach as deep as 3.5 m, making difficult the estimation of soil water holding capacity. Also, direct determination of soil water content close to the root zone is complicated due to the heterogeneity of soils, water distribution close to the root zone (drip irrigation) and uncertainty about root depth. Furthermore, the implementation of weather based methods such as evaporation pan corrected by a suitable Kc for irrigation scheduling, showed to recommend excessive irrigations in the order of 23 irrigations (T1), which are 6 fold higher compared to the number of irrigations applied for T3 (for the three seasons studied). Furthermore, these methods do not include the feedback effects on soil water depletion on transpiration through stomatal control, making them unsuitable to estimate water use under stress conditions. The use of midday ψ_S as a physiological index, demonstrated to be a suitable way to perform irrigation scheduling on grapevines under RDI, since it considers soil–plant–atmosphere factors. A mild water stress of down to −1.2 MPa, for the cv. Cabernet Sauvignon under RDI (T3), showed to be the most effective threshold to optimize soil water availability, irrigation scheduling, yield and grape quality. Therefore, the use of midday Ψ_S offers an alternative method to apply accurate irrigation scheduling criteria with a strong physiological component to manage water supply, not only to control general irrigation treatments, but also to manage more specialised irrigation techniques such as RDI. Finally, a real regulation of the deficit imposed to the vines can be achieved using midday ψ_S to obtain maximum WUE, grape quality and yield. Additionally, lower thresholds (below −1.2 MPa found for T3) need to be tested in the future to obtain the maximum stress level that these grapevines can endure before starting to compromise yield and berry quality.

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