

Effect of water application on wine quality and yield in 'Carménère' under the presence of a shallow water table in Central Chile

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ABSTRACT

Chile is the world's leading producer of 'Carménère' (*Vitis vinifera* L.), which in turn is an important variety in Chile, where vineyards are typically grown under irrigated conditions and a large percentage are located in valleys with similar water table levels to those of the study area. Different irrigation management strategies have been used to improve wine quality, such as water stress and deficit irrigations, but the presence of a water table has not been considered in extant literature. This study analyzes the effects of the irrigation regime on grape yield and wine quality when a shallow water table is located between 1.5 to 2.2 m depth during the irrigation season. Five applied water treatments: 0%, 20%, 40%, 75%, and 100% of estimated vineyard evapotranspiration (ET_c) were applied in an own-rooted 'Carménère' vineyard located in the Peumo Valley (Chile) during three consecutive seasons (2004-2005 to 2006-2007). Applying 1400 to 9400 m³ ha⁻¹ per season (100% ET_c) had no substantial effect on the measured quality parameters, although grape production in the treatment without irrigation (0% ET_c) was significantly reduced. Applying water at 20% to 40% ET_c produced high yield (13 to 16 t ha⁻¹), double the historical mean production, and high quality wine with the presence of a water table close to the bottom of the root zone.

Key words: Drip irrigation, grape production, stem water potential, total polyphenol index, vineyard, *Vitis vinifera*.

INTRODUCTION

While climate change has the potential to impact most forms of agriculture, wine grape (*Vitis vinifera* L.) production is particularly sensitive to environmental and management practices because wine is strongly associated with regional and varietal characteristics, which, in turn, depend on seasonal weather conditions (Mira de Orduña, 2010). Although vineyards irrigation is not a common practice in some productive areas of the world, vineyards in Chile are typically grown under irrigated conditions to manage wine and grapes quality.

Junquera et al. (2012) pointed out that it is very important to understand the effects of applying different volumes of water to vines, as well as irrigation timing on yield and berry composition. A gradual and moderate water deficit is thus normally preferred in cool areas to control shoot vigor and allow sugars to be transferred to the clusters. This results in better ripening, higher °Brix value, lower malic acid concentrations, and more intensely colored wines (Spring and Zufferey, 2009). Less severe water deficits may be preferred in warm regions with long growing seasons (Junquera et al., 2012).

Williams (2012) showed that berry weight in a Merlot grapevine and vine yields increased significantly as volumes of applied water increased, while sustained deficit irrigation can be a way to increase fruit quality. However, a significant yield reduction measured in this vineyard indicates that irrigation deficit is not economically sustainable in the San Joaquin Valley, California. Grape production and quality for winemaking could require a special irrigation strategy that consists in applying less water than is required by the grapevine during some periods of its phenological stages, such as after fruit set to veraison, combined with leaf removal (Cook et al., 2015).

The wide variety of approaches presented in different papers shows that wine-producing vineyards are complex systems where optimal irrigation strategies are difficult to generalize (Ortega-Farías et al., 2012). The relationship between water and grapevines – particularly the effects of water stress as indicated by low leaf water potential – is well documented and reviewed (Deloire et al., 2004). Different irrigation strategies (regulated deficit irrigation and partial root irrigation) and their effects on yield, grape and wine quality, as well as water use efficiency, are discussed by Medrano et al. (2015), who conclude that it is possible to reduce plant water use, maintaining or improving fruit quality without reductions in yield. Junquera et al. (2012) mentioned that grapevine plants responded to environmental conditions and events that took place during previous growing

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seasons. Therefore, they suggest evaluating at least 3 yr to obtain a reasonable response and reliable information under different irrigation strategies.

The occurrence of groundwater under vineyards (a shallow water table with temporal variations of depth) has not been considered in assessing irrigation strategies. In fact, in the upper area of Peumo Valley, which is part of the 2201 ha of vines in the Cachapoal Valley (Wines of Chile, 2015), there is a water table ranging from a 2.5 m depth permanently recorded in winter, to approximately 1.5 m in spring and summer under well drained soils (Arumí et al., 2013). These situations are common in several watersheds in Central Chile, where wine production under irrigation is important. Salgado (2000) estimated that 50% of Central Valley soils in Chile are imperfectly drained with a water table depth from 0.9 to 1.5 m; and only 15% are moderately well drained soils with water tables greater than 1.5 m depth. Although many vine roots are found in the first meters of soil, they have also been found at depths of 2 to 6 m (Smart et al., 2006), suggesting a relationship between root depth and groundwater occurrence. Therefore, it is important to consider this in the case of vine production and wine quality as vines can uptake water from shallow water tables, offsetting deficit irrigation practices.

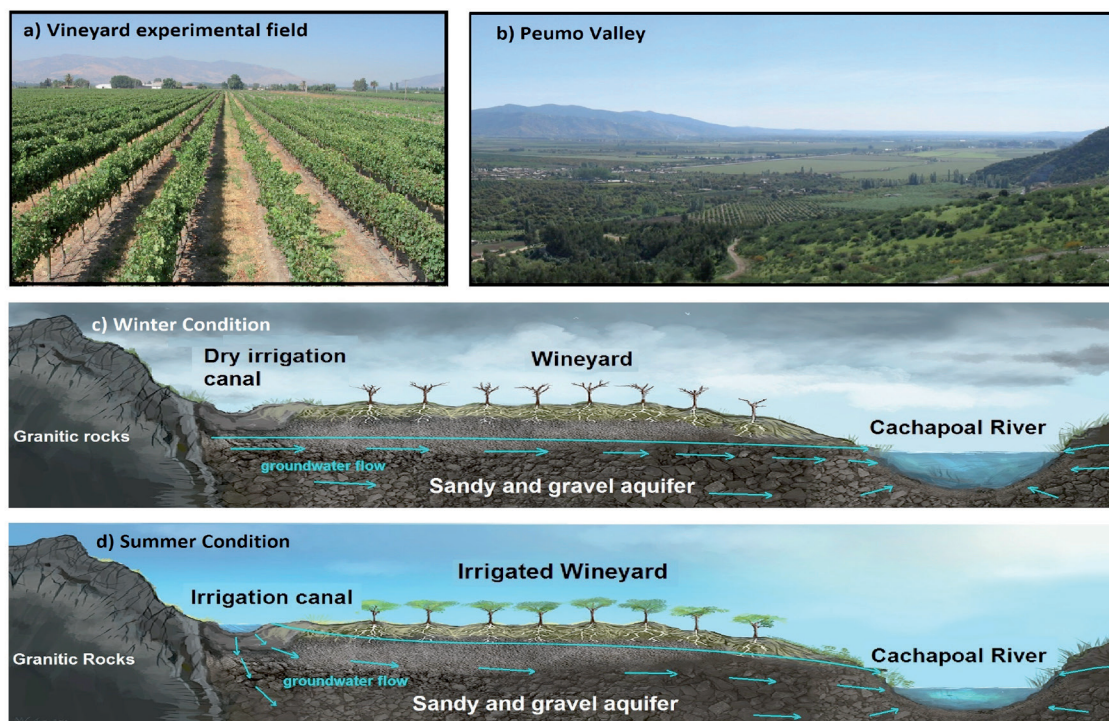
The aim of the present study was to evaluate the effects of applying five water volumes in ‘Carménère’ grape production and wine quality during three consecutive irrigation seasons in the Peumo Valley, located at the lower section of the Cachapoal Valley (Chile), under conditions of a water table located from 1.5 to 2.2 m depth in spring and summer.

MATERIALS AND METHODS

General background of the study area

The research study was carried out at the Concha y Toro Vineyard (71°10'45" W, 34°22'44" S; 170 m a.s.l.), located in the upper Peumo Valley (160 km²), which is part of the lower part of the Cachapoal River basin, Chile. The study lasted three seasons (2004-2005, 2005-2006, and 2006-2007) and was conducted in a drip-irrigated vineyard (*Vitis vinifera* L.) with own-rooted ‘Carménère’ vines established in 1997; vine spacing between rows was 2.5 m and vine spacing within the row 1.5 m. The zone has a sub-humid Mediterranean climate with a mean maximum temperature of 32 °C in January, an annual mean of 14 °C, and annual mean rainfall of 564 mm with a standard deviation of 236 mm, with 92% annual amounts during May to September for the period 1960 to 2006 (Arumí et al., 2013). There is high heat accumulation (heliothermal index, HI = 2441), which is a suitable condition for ‘Carménère’ (Montes et al., 2012). The soil is Typic Xerochrepts, alluvial origin, surface slope about 0.4% to the south, with a clay loam texture at the surface that varies to sandy loam at 1.0 m depth, and coarse sand, gravel and stone at depths greater than 1 m; soil bulk density 1.66 Mg m⁻³ at the surface to 1.61 Mg m⁻³ at 1.0 m depth, field capacity 0.329 m³ m⁻³ at the surface to 0.315 m³ m⁻³ at 1.0 m depth, permanent wilting point 0.230 m³ m⁻³ at the surface to 0.209 m³ m⁻³ at 1.0 m depth. Figure 1 shows a field layout of the general condition of the Peumo area and the site of experiment. The training system was vertical shoot positioning, double cordon cane pruning with north-south row orientation. All treatments were pruned in winter (June-July) with the

Figure 1. Field layout of the study area in Peumo Valley (Chile). (a) ‘Carménère’ vineyard; (b) general overview of Peumo Valley; (c) conceptual model including presence of a shallow water table located at 2.5 m depth during winter with groundwater levels controlled by the river head; (d) presence of a shallow water table located at 1.5 to 2.2 m depth during the irrigation season, where the water table rises by recharge from the unlined irrigation canals and irrigation losses.



same number of spurs per plant: 15 spurs in the 2004-2005 season and 25 spurs in the next two seasons. The historical mean yield for this site has varied between 5.1 and 8.6 t ha⁻¹ and the irrigation period lasted from November to March, with variable volumes of applied water (2000 to 4000 m³ ha⁻¹ season⁻¹).

Water application treatments and viticulture practices

Treatments consisted of five applied water volumes based on reference evapotranspiration estimated from daily measurements of a standard evaporation pan (USWB Class A) located in the vineyard. In this study, vineyard evapotranspiration was calculated as:

$$ET_c = E_p K_p K_c \quad [1]$$

where ET_c is estimated vineyard evapotranspiration (mm d⁻¹), E_p is mean pan evaporation of the previous week (mm d⁻¹), K_p is the pan coefficient (assumed to be 0.8; Doorenbos and Pruitt, 1977), and K_c is the crop coefficient.

Theoretical vine water demand, $V_{(ET_c)}$, was obtained by considering the relationship between the shaded area and evapotranspiration based on Fereres et al. (1982), and following the calculations outlined in Holzapfel et al. (2015):

$$V_{(ET_c)} = E_p K_p K_c \left(\frac{1.28 P_c + 0.11}{E_f} \right) H L \quad [2]$$

where $V_{(ET_c)}$ is expressed in L d⁻¹ plant⁻¹, P_c is an estimated dimensionless plant canopy coverage ($0.1 < P_c < 0.7$), determined by measuring the shadow projected by the vine on the soil at solar noon, H is the distance between rows (2.5 m), L is within-row plant spacing (1.5 m), and E_f is assumed irrigation application efficiency (0.95). The control treatment was irrigated assuming a K_c of 1.0, to ensure that such treatment was never short of water.

The 2003-2004 season was used as an adjustment period, during which the irrigation system was modified to obtain five irrigation treatments. The four applied water treatment levels were vines drip-irrigated at 100%, 75%, 40%, and 20% of estimated ET_c (Equation [1]) once irrigation started. Water applied after veraison was reduced to 50% in each treatment. A fifth treatment without irrigation (0% ET_c) was included to evaluate the effect of a water table during the irrigation season. In accordance with the vineyard's irrigation management protocols, water was applied in each season from the end of November to late March, every day from Monday to Friday with drip irrigation and two 4 L h⁻¹ auto-compensated drip emitters per plant, which were placed at 0.3 m from the trunk on both sides.

Fertilizer was applied by fertigation at three stages (initial berry growth, veraison, and post-harvesting) throughout the four irrigation seasons at a total annual rate of 31.8 kg N ha⁻¹ ((NH₄)H₂PO₄, KNO₃ and CO(NH₂)₂), 13.1 kg P ha⁻¹ ((NH₄)H₂PO₄), 22.0 kg K ha⁻¹ (K₂SO₄), and complemented with H₃BO₃ (2.0 kg ha⁻¹) and ZnSO₄ (1.5 kg ha⁻¹). The 0% ET_c treatment was fertilized by hand twice per season (grape

growing and post-harvesting stages) with the same total annual rate as the other four treatments.

Water table depth, soil water content, matric potential and vineyard stem water potential

As part of a monitoring water table network, six observation wells with 5 cm diameters steel pipe were installed at the experimental vineyard field, located at the upper part in the Peumo Valley. Data were collected monthly and more frequently during the irrigation season (October to April), according to the procedure presented by Arumí et al. (2009). Also, groundwater levels were measured in a deep well located 3 km west from the vineyard field, at the Pozo Estadio Peumo station (DGA, 2016).

Soil water content was measured at six depths (0.1, 0.2, 0.3, 0.4, 0.6, and 1.0 m) in each treatment plot with a Delta-T profile probe (Model PR 1) and meter (Model HH2; Delta-T Devices Ltd., Cambridge, UK), calibrated on site. Fiberglass access tubes were installed 10 cm from the drippers in the wetted zone. Measurements were taken just before daily irrigation, three times per week and every 15 d. Matric potential was estimated by the soil water retention curve using the model proposed by Campbell (Campbell and Norman, 1998).

Stem water potential was measured at midday (between 12:00 and 15:00 h local time) with a Schollander pressure pump (model 3005 Soil Moisture Equipment Corp., Santa Barbara, California, USA). For each replicate, measurements were taken on two healthy and mature sun-exposed leaves located in the middle third of the plant, twice a week every 15 d during the irrigation season. Leaves were placed in plastic bags covered with aluminum foil 2 h before the measurements.

Grape yield, physical-chemical analysis, microvinification and sensorial evaluation of wine

Grapes for each treatment were harvested manually by row at maturity, late in the season in May, based on the winery's protocol to reduce herbaceous strains. From the 12 vines monitored in the central row of each experimental unit, yield, number of clusters per vine, cluster weight and berry diameter were measured. Five days before harvest, 100 berries per treatment were collected and taken to the Concha y Toro Laboratory to determine technological maturity (soluble solids, pH and total acidity) using the analytical methods recommended by OIV (2005). Phenological maturity (total polyphenol index, TPI) was determined using a spectrophotometer (Genesys 5 UV-Vis, Thermo Scientific, Waltham, Massachusetts, USA) in a 1 cm quartz cuvette (Ribéreau-Gayon et al., 2006). The wavelength used was 280 nm.

The grape fermentation process for winemaking was carried out in five 50 L steel tanks (one for each irrigation treatment). Micro-fermentation was conducted in the

same way for all treatments by following Concha y Toro's standard practices for small-scale red wine production. At the end of the micro-fermentation process, an oenological sensory panel made up of four professional tasters from the Concha y Toro Winery conducted blind tasting to evaluate wine quality. The aspects considered were visual (clarity, color intensity and tint), olfactory (intensity, finesse and harmony), and taste analyses (intensity, body, harmony, persistence and final sensation). The scores of all the judges were averaged for each wine, scale 1 to 100, according to the following pattern: Icon (100 to 95), Super Premium (95 to 90), Premium (90 to 80) and Varietal (80 to 70).

Seasonal characterization

Meteorological data were obtained from a Vantage Pro 2 weather station (Davis Instruments, Hayward, California, USA) located at the experimental site during the experiment (Table 1). Cumulative thermal time (τ) for phenological stages was estimated from daily maximum (T_{max}) and minimum (T_{min}) air temperatures:

$$\tau = \sum_{i=1}^n \left(\frac{T_{max_i} + T_{min_i}}{2} - 10 \right) \Delta t \quad [3]$$

where τ is reported in degree-days above 10 °C and Δt is the time increment (1 d). The summation of the diurnal thermal amplitude $\Sigma \Delta T_{max-min}$ was also calculated from the differences between daily T_{max} and T_{min} air temperatures:

$$\Sigma \Delta T_{max-min} = \sum_{i=1}^n (T_{max_i} - T_{min_i}) \quad [4]$$

where $\Sigma \Delta T_{max-min}$ is expressed in °C. Daily mean vapor pressure deficit (VPD_{mean}) for two main grapevine phenological stages (before and after veraison) was estimated from saturation vapor pressure at daily mean air temperature (T_m) minus mean actual vapor pressure calculated with daily maximum and minimum relative humidity. Vapor pressure deficit (VPD) at solar noon was also estimated using the expression $VPD = e_0 (1-rh)$, where e_0 is the saturated vapor pressure at the actual air temperature and rh represents relative humidity measured at the same time by the weather station.

Table 1. Climatic variables for two main 'Carménère' grapevine phenological stages during three growing seasons.

Variable	Growing seasons		
	2004-2005	2005-2006	2006-2007
τ Fruit setting-veraison, degree-days	264	277	266
τ Veraison-harvest, degree-days	1089	1233	1084
$\Sigma \Delta T_{max-min}$ fruit setting to veraison, °C	541	546	532
$\Sigma \Delta T_{max-min}$ veraison to harvest, °C	2627	2978	2537
Daily VPD_{mean} fruit setting to veraison, kPa	1.38	1.42	1.37
Daily VPD_{mean} veraison to 30 DPH, kPa	1.33	1.44	1.14
Seasonal rainfall November to harvest, mm	196	42	39
Cumulative rainfall 30 DPH, mm	137	25	1
Annual rainfall May to April, mm	462	755	686

τ : Cumulative thermal time base 10 °C, $\Sigma \Delta T_{max-min}$: diurnal thermal amplitude summation, VPD_{mean} : mean daily vapor pressure deficit, DPH: days prior to harvest.

Fruit set to veraison is from the last week of November to last week of January. Harvest time is during the first week of May.

Experimental design

The experimental design was a randomized complete block with five applied water treatments: 100%, 75%, 40%, 20%, and 0% of estimated ET_c with K_c 1.0 (Equation [1]). Blocks were established across rows with irrigation treatments randomly assigned to three specific contiguous rows within each block. Each block was replicated four times. Each experimental unit included three contiguous rows of 12 vines in a row: one treatment data row and two border rows (36 vines in total). Samplings for each of the tested parameters were carried out in the central row of each experimental unit. The border rows were between each adjoining treatment. The data collected were analyzed by ANOVA and the means were compared with Tukey's multiple range test ($P \leq 0.05$).

RESULTS AND DISCUSSION

Water table depth

Shallow water levels drop during winter and rise after the opening of irrigation canals in the experimental vineyard field (Figure 2). Water table is located between 1.5 to 2.2 m depth during the irrigation season, when groundwater is recharged mainly by seepage from the irrigation canal network after the beginning of irrigation canal operations in September. On the other hand, a deeper well located 3 km west of the vineyard, also shows slight increments in groundwater during the irrigation season that corresponds to the shallow wells. Thus, it is possible to establish that the effect of canal and irrigation seepage not only have local effects. Therefore, the valley exhibits particular features in terms of hydrological processes, as summer water levels are shallower than those occurring for valleys without dense unlined channel networks (Arumí et al., 2013). Also, water table influence on production would challenge current practices on modeling the effects of climate change and agricultural water management on yield, grape and wine quality (Mira de Orduña, 2010).

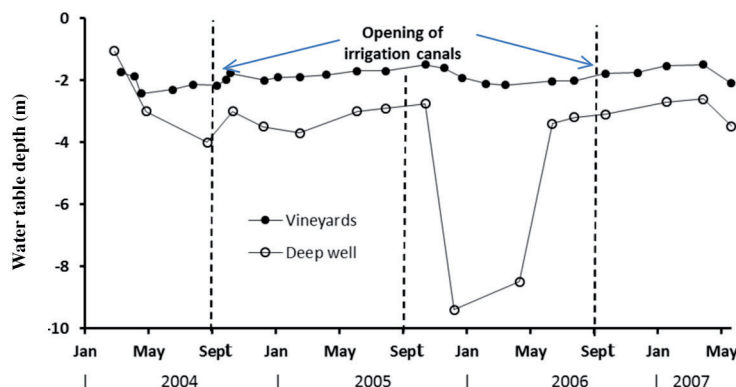
Applied water

Volumes of applied irrigation water to the vineyard were similar in each season (Table 2); however, the 2004-2005 season shows the largest amount of applied water because irrigation started earlier in this season (mid-November) due to lower annual precipitation. The amount of water that is normally applied to vines in Chile under semi-arid conditions ranges from 2500 m³ ha⁻¹ (Acevedo-Opazo et al., 2010) to approximately 4500 m³ ha⁻¹ (Ferreira et al., 2002) for non-stressed treatments. These values approximate the 40% ET_c treatment values found in this research study.

Matric potential and midday stem water potential of vineyard

The matric potential varied greatly during the different periods of the study due to localized irrigation (drip irrigation). For the 2005-2006 season, the lowest matric

Figure 2. Observed groundwater levels in the experimental vineyard and in a deep well located 3 km West from the vineyard, from March 2004 to May 2007.



potential values were between the 0.1 and 0.4 m depths for irrigated treatments (Figure 3), which indicated increased water extraction by roots; it was not possible to observe differences in matric potential associated with the four different applied water volumes. However, significant differences were found between the four irrigated treatments and the treatment without irrigation (0% ET_c), in practically all evaluated data. The treatment without irrigation maintained matric potentials less than -1.0 MPa during all the season in the soil profile. For the matric potential in the zone of the wet bulb, it was relatively constant over time and even under lower applied water volumes that could show a decreasing trend. Similar behavior is repeated in the other two seasons (data not shown).

Regardless of irrigation treatments, daily data for midday stem water potential of vineyards tends to fluctuate between -0.2 and -0.5 MPa (Figure 4) and nonsignificant differences

were found among treatments in almost all evaluated data. It is important to point out that stem water potential values, measured at midday during the three seasons in the present study, were higher than the threshold proposed by Van Leeuwen et al. (2009) for grapevines as an indicator of no water deficit (> -0.6 MPa). Jara-Rojas et al. (2015) reported values of -0.4 to -1.6 MPa for a 'Carménère' commercial vineyard located in the Talca Valley, Chile, drip-irrigated with 2570 to 3140 m³ ha⁻¹ season⁻¹, during a 3-yr experiment. Additionally, Williams (2012) obtained values of -1.3 MPa and -0.6 MPa for 'Merlot' grapevines irrigated at 40% and 120% of estimated vineyard evapotranspiration, respectively.

Water stress was not found in the present study, not even in the treatment without irrigation. This situation would indicate permanent and effective activity of the vine plants' deep root systems, and that the presence of a shallow water table would permit root water uptake as sub-surface irrigation (Chai et al., 2016). The presence of a shallow water table in Chile has only been described by Fredes et al. (2010) for 'Carménère' grapevines (phreatic level depth at 2 m), but this background information has not been considered in most authors' reports.

Another explanation for these high stem water potential values could be related to VPD values measured at midday (Figure 4), which ranged between 2.73 and 4.49 kPa (mean 3.51 kPa). These stem water potential values are comparable to those indicated by Williams and Baeza (2007), who obtained stem water potential values between -0.3 and -0.5 MPa when VPD varied between 1.0 and 4.0 kPa for four fully-irrigated cultivars grown at five locations in California. However, when VPD values increased to 6.0 kPa in California, stem water potential decreased to -0.8 MPa.

By excluding cloudy days (days of year 350 and 38), it is possible to detect a general decreasing trend in stem water potential for the four irrigation treatments as the seasons progress (Figure 4). The decrease in stem water potential could be caused by a 50% reduction in applied water after veraison (day of year 26), which is a water management criterion to improve the quality of wine grapes (Ferreira et

Table 2. Volume of applied irrigation water, grape production, total polyphenol index and wine evaluation score by expert panel of 'Carménère' grapevine for three seasons and five irrigation treatments.

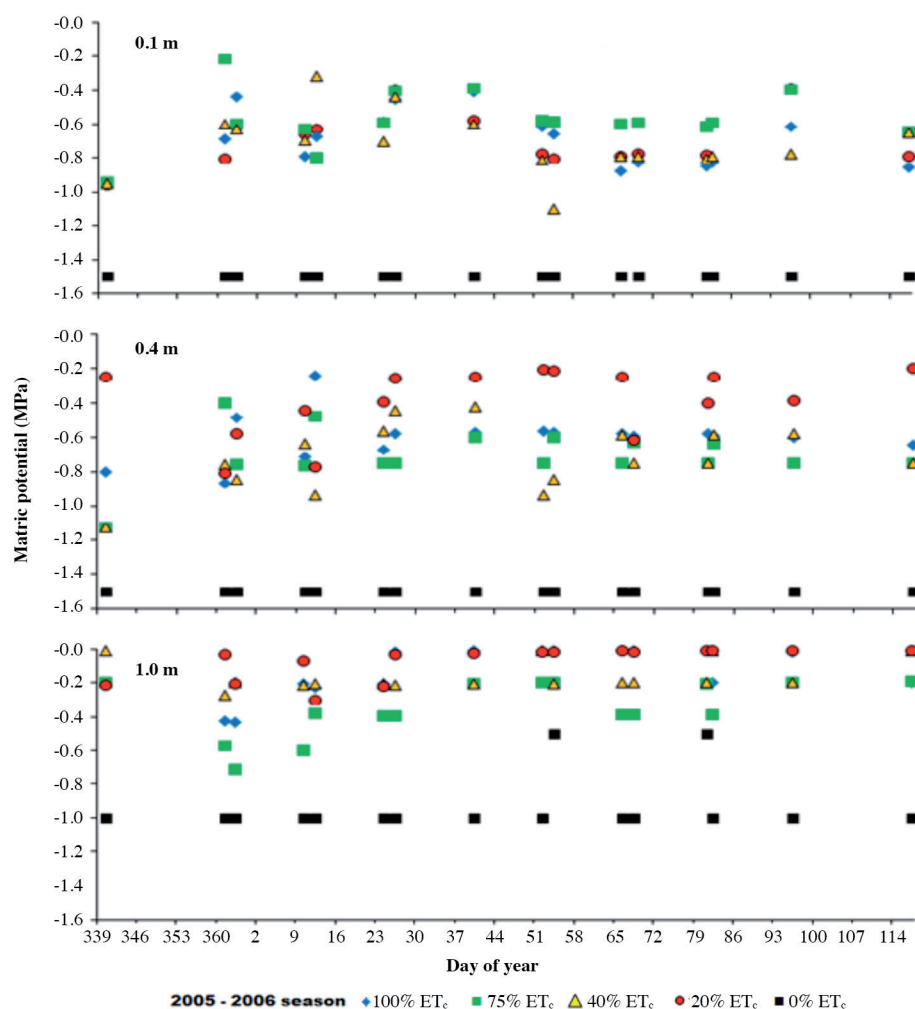
Season	100% ET _c	75% ET _c	40% ET _c	20% ET _c	0% ET _c
Volume of applied irrigation water (m ³ ha ⁻¹ season ⁻¹)					
2004-2005	9366	7024	3746	1873	0
2005-2006	7281	5461	2913	1456	0
2006-2007	6788	5092	2716	1358	0
Grape production (kg ha ⁻¹)					
2004-2005	9205a	9221a	10277a	8975a	7272b
2005-2006	18032a	15177a	16788a	14170a	7488b
2006-2007	13025a	13782a	12750a	12984a	6099b
Total polyphenol index					
2004-2005	21.1b	19.2b	21.9b	23.2b	32.1a
2005-2006	49.5a	46.0a	46.4a	47.7a	53.0a
2006-2007	49.8a	46.4a	46.7a	47.0a	54.0a
Wine evaluation score (1 to 100)					
2004-2005	57	71	77	53	85
2005-2006	86	85	87	89	90
2006-2007	87	89	90	91	92

Different letters in the row mean a significant difference at $P \leq 0.05$ in the Tukey test.

ET_c: Estimated vineyard evapotranspiration.

Wine evaluation score: Icon 100 to 95, Super Premium 95 to 90, Premium 90 to 80, Varietal 80 to 70.

Figure 3. Seasonal course of matric potential just before irrigation for five volumes of applied water treatments on vineyard ‘Carménère’ plants, at depths of 0.1, 0.4, and 1.0 m for the 2005-2006 season. Applied water was reduced to 50% in each treatment after veraison (day of year 26). Data are means of four replicates.



ET_c: Estimated crop evapotranspiration.

Applied water treatments: ♦100% ET_c, ■75% ET_c, ▲40% ET_c, ●20% ET_c, and ■0% ET_c (without irrigation).

al., 2002; Junquera et al., 2012) and would influence root water uptake. Other factors that could have caused lower stem water potential at the end of the period, especially in the 2005-2006 season, were the higher daily VPD_{mean}, thermal time (τ) and diurnal thermal amplitude summation ($\Sigma\Delta T_{max-min}$), which occurred in this season after veraison (Table 1). However, it is important to mention that the response of grapevine to VPD is unclear. In fact, several authors mentioned that VPD has an important effect in the stem water potential combined with stomatal control, air temperature, solar radiation and soil water content (Prieto et al., 2010; Chaves et al., 2010). In our study, the high stem water potential values could be attributed to stomata control and/or an active root water uptake from water table.

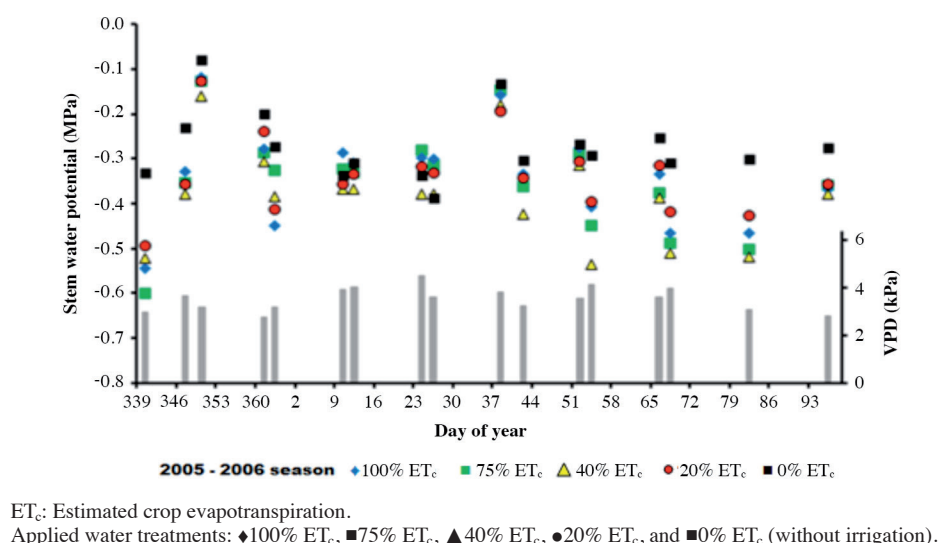
Fruit production

Prior to our research in the study area, historical irrigated grape yield ranged from 5100 to 8600 kg ha⁻¹ as usual management assumes that low yields led to high quality

wine. For each season, there were nonsignificant differences in yield among the four applied water treatments (Table 2). However, a large and significant difference appears between the four irrigation treatments and the treatment without irrigation (0% ET_c) for all seasons. Thus, the effect of irrigation increases production by approximately 30% for the 2004-2005 season. For the 2005-2006 and 2006-2007 seasons, production under irrigation treatments was twice that of treatment without irrigation. Thus, a plausible explanation is that shallow-water table conditions explain about 50% of the production, offsetting deficit irrigation practices.

Grape production in the 2004-2005 season was similar to the historical range of 9000 to 11 000 kg ha⁻¹ reported by Fredes et al. (2010) for a ‘Carménère’-growing vineyard in the Curicó Valley, Chile. The same authors obtained yields between 12 200 and 29 295 kg ha⁻¹ when evaluating the effects of cluster thinning and pruning weight combinations at the same location on soil with better growth potential and

Figure 4. Daily stem water potential and vapor pressure deficit (VPD) at midday for five irrigation treatments on vineyard ‘Carménère’ plants, for the 2005-2006 season. Days of year 350 and 38 correspond to cloudy days. Veraison began day of year 26. Data are means of four replicates and eight measurements.



a water table depth of approximately 2 m. Likewise, Jara-Rojas et al. (2015) informed yield of 9000 to 11 000 kg ha⁻¹ for a drip-irrigated ‘Carménère’-growing vineyard in the Talca Valley, Chile. Higher yield in the four irrigated treatments, as compared with that without irrigation during the three seasons, is due to a number of established clusters per plant (41 to 49) larger than in the treatment without irrigation (28 to 37), larger cluster weight at harvest (105 to 178 g) than in the treatment without irrigation (74 to 95 g). Although berry diameters at harvest did not show any significant differences between treatments during the three seasons, the 2005-2006 season exhibits the highest mean berry diameters values (14.2 mm) and the 2004-2005 season the lowest (11.7 mm). This is important because berry size influences wine quality where a higher grape skin/volume ratio is desirable.

Effect of applied water and must characteristics

High soluble solids values were obtained at harvest for all treatments in the three seasons (23.0 to 26.9 °Brix), especially in 2005-2006; these values are higher than the 24 °Brix obtained for the same vine stock in the Maule Valley, Chile (Obreque-Slier et al., 2010), and the 24 to 25 °Brix obtained in the Curicó Valley, Chile, for low vigor and low yield vine stocks (Fredes et al., 2010). However, values of up to 25.7 °Brix for a late harvest were obtained in ‘Carménère’ grown in the Maipo Valley, Chile (Obreque-Slier et al., 2012). Although delaying the harvest of ‘Carménère’ is a common practice to reduce herbaceous strains, high soluble solids contents in the 2005-2006 season (25.0 to 26.9 °Brix) could indicate that the fruit was overripe or partially dehydrated on the vine due to excessive heat. These values could be due to the climatic conditions of this season, which had a higher τ , diurnal thermal amplitude

summation $\Sigma\Delta T_{max-min}$, and daily mean VPD for the veraison and harvest phenological stages, along with the almost complete lack of rainfall during the growing season (November 2005 to harvest in May 2006) and during the last 30 d before harvest (Table 1).

Regardless of higher fruit production, the larger number of clusters per plant, greater berry diameter, must acidity and pH levels were generally within the normal range at harvest in the 2005-2006 season. In general, total must acidity exhibited low values (2.2 to 3.3 g L⁻¹ H₂SO₄) while pH values were higher (3.81 to 4.05) in the three seasons, which are characteristics of ‘Carménère’. Likewise, in each of the three seasons, levels of soluble solids content, total must acidity, and pH showed no differences among treatments (data not shown), which could be attributed to other factors than irrigation volumes, such as microclimate and terroir features.

Even though the results of the 2004-2005 season showed the smallest berry diameters, the low soluble solids content and low must acidity were within the optimal range at harvest; however, the total polyphenol index (TPI) was the lowest out of the three study periods (Table 2). This low TPI value could be related to high rainfall during the final 30 d before harvest (Table 1), which may produce grape fungi, affecting quality (Briceño et al., 2009). Additionally, it can be seen that in the treatment without water application the TPI tends to be the highest in each season (Table 2). The importance of high TPI values in the must is in their relationship with the positive effects on the future quality of the wine (Choné et al., 2001). In comparison with other red wine cultivars, the TPI values obtained in the 2005-2006 and 2006-2007 seasons are within the range shown by other authors (Choné et al., 2001; Rfo Segade et al., 2008). However, in the 2004-2005 season, only the treatment without irrigation showed TPI values (32.1) close to the minimum.

Regardless of the higher fruit production, the larger number of clusters per plant and larger berry diameter – which could have negatively affected the quality – the must obtained in the 2005-2006 season was of higher quality, according to the measured variables and TPI levels. This could be due to the climatic conditions of this season, with a greater τ and diurnal thermal amplitude summation $\Sigma T_{max-min}$ over the phenological stage from veraison to harvest, and the almost complete lack of rainfall during the growing season (November 2005 to harvest 2006) and during the last 30 d before the harvest period (Table 1).

Sensorial analysis of wine

Values of the wine evaluation conducted by the panel of oenologists of the Concha y Toro Winery are shown in Table 2. Results were relatively similar for two of the three seasons with values greater than 80 (Premium quality). Although the treatment without irrigation received a high score, the lower values of the 2004-2005 season could be caused by the high rainfall that occurred during the month prior to harvest (Table 1); this can produce grape fungi and affect quality for red grapevine cultivars in Chile (Briceño et al., 2009). Taste panel results indicate that wine quality, with the exception of the 2004-2005 season, was not clearly affected neither by grape production nor irrigation rate. Wine quality ratings for treatments 20% and 40% ET_c were classified as similar to the treatment without irrigation, but doubling the yield (Table 2). Even the wine under the treatment 100% ET_c obtained high scores, but this treatment exhibits inefficient water use. Given the climatic and soil conditions of the Peumo Valley, it is possible to increase grape production levels, as in the last two seasons, without reducing wine quality. Thus, it is possible to infer that the 13 000 to 16 000 kg ha⁻¹ range could be obtained, with a low applied water level of 20% to 40% of the theoretical or potential water required by the vineyard (100% ET_c) and with a 50% reduction in irrigation water after veraison.

CONCLUSIONS

Given the Peumo Valley conditions, a high-quality ‘Carménère’ wine with greater than normal production for areas with similar characteristics could be achieved under irrigation conditions. Grape production values could range from 13 to 16 t ha⁻¹ with Premium quality. Taking the climatic and agro-ecological conditions into account, as well as the presence of a water table at a 1.5 to 2.2 m depth during the irrigation season, maximum yield values - double the historical mean production - and high quality wine could be produced by applying 20% to 40% of potential irrigation water required by the vineyard (100% of estimated vineyard evapotranspiration). This could be obtained under irrigation with the presence of a shallow water table, even with a large number of clusters per vine and high cluster weight. The applied water volume ranging from 1400 to 9400 m³ ha⁻¹

per season had non-significant differences on ‘Carménère’ yield, although a treatment without irrigation shows a significant reduction in yield.

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