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RESEARCH ARTICLE

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Evaluation of potential irrigation water savings by assessing the soil water balance in a vineyard in central Chile

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Abstract

The main aim of this study was to evaluate the potential savings of irrigation water by assessing the soil water balance during the growing season in a wine vineyard in the Maule region, Chile. This study provides insights into the influences of different irrigation water applications on soil water status and its potential effects on grape yields, water use efficiency (WUE) and the cost of irrigation to help improve irrigation practices in the region and other similar Mediterranean regions. The field experiment compared three levels of irrigation water applied: current irrigation of the vineyard (T_0) and two deficit irrigation treatments with reductions to 75% (T_1) and 50% of the irrigated water (T_2). The measurements included volumetric soil water content, shallow groundwater table, canopy cover and grape yield at harvest during the entire growing season (October 2017 to April 2018). We found a potential reduction of 25% or 50% in the current irrigation system while maintaining the grape yield, increasing the WUE and reducing the cost of irrigation. Consideration of the water stored in the soil by the accumulation of rainfall in the winter season and the potential for capillary rise of shallow groundwaters is crucial for adjusting irrigation to vine water requirements.

KEYWORDS

bulk wine, deficit irrigation, soil water content, water use efficiency (WUE)

Résumé

Cette étude visait à évaluer les économies potentielles d'eau d'irrigation en évaluant le bilan hydrique du sol pendant la saison de croissance dans un vignoble de la région de Maule, au Chili. L'étude donne un aperçu des influences exercées par des différentes applications de l'eau d'irrigation sur l'état de l'eau du sol et de ses effets potentiels sur les rendements en raisin, l'efficacité de l'utilisation de l'eau (WUE) et le coût de l'irrigation pour aider à améliorer les pratiques d'irrigation dans la région et dans d'autres régions similaires dans des

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conditions climatiques méditerranéennes. L'expérimentation menée sur le terrain a comparé trois niveaux d'eau d'irrigation appliquée: irrigation actuelle du vignoble (T_0), et deux traitements d'irrigation déficitaire de réduction à 75% (T_1), et à 50% de l'eau irriguée (T_2). Les mesures comprenaient la teneur volumétrique en eau du sol, la nappe phréatique peu profonde, le couvert forestier et le rendement des raisins à la récolte, pendant toute la saison de croissance (octobre 2017-avril 2018). Nous avons trouvé une réduction potentielle de 25% ou 50% de l'irrigation actuelle, tout en maintenant le rendement des raisins, en augmentant le WUE et en réduisant le coût de l'irrigation. La prise en compte de l'eau stockée dans le sol par l'accumulation des précipitations en hiver et le potentiel de remontée capillaire des eaux souterraines peu profondes est cruciale pour ajuster l'irrigation aux besoins en eau de la vigne.

MOTS CLÉS

vin en vrac, irrigation déficitaire, teneur en eau du sol, efficacité d'utilisation de l'eau (WUE)

1 | INTRODUCTION

The sustainability of grapevine production largely needs serious consideration regarding the environmental impact of the large amount of freshwater withdrawn and consumption for irrigation of commercial vineyards, especially in relatively drier climatic regions such as Mediterranean areas in central Chile. Consumers and wholesalers are increasingly demanding more sustainable food products. Water will be a major constraint for food production in coming decades, and to address water scarcity, a focus on increasing overall water use efficiency (WUE) is recommended (Permanhani et al., 2016; Rijsberman, 2006).

Increased sustainability of water resources for vineyards can be achieved by reducing the total amount of water used for irrigation, which does not generally mean a certain reduction in grape yield (Medrano et al., 2015). Herath et al. (2013) studied the impact of water use through the wine production process across different regions of New Zealand and found that the quantity of water used in the winery phase was very small compared to that used in the grape-growing stage of the vineyard. This suggests a greater scope of potential water savings by improving soil water balance assessments to improve irrigation practices in vineyards. A robust analysis of irrigation practices requires a sound understanding and measurements of different soil water balance components and their potential effects on plant growth and yields under field conditions. The soil water balance during the growing season considers inputs from irrigation, precipitation, soil storage within the profile and capillary rise and outputs from evapotranspiration, drainage or deep percolation and surface runoff (Or et al., 2012). These parameters are determined by site-specific soil water environments and management practices. Thus, in vineyard production under Mediterranean conditions, there are several ways of assessing available soil water and estimating vine water status (White, 2015). In addition, careful guidance is required to manage the synergistic interactions between water and nutrient supplies and vine growth to ensure efficient grape yield and quality in commercial vineyards (Keller, 2005).

Deficit irrigation (DI) maintains some degree of water deficit, leading to maintaining or increasing grape quality at the cost of reducing grape yield but substantially reducing the amount of water applied (Chapman et al., 2005; Cifre et al., 2005; Permanhani et al., 2016). In vineyards, irrigation and water-saving techniques are considered adaptation measures under climate change and water-limiting conditions (Azorín & García, 2020; Naulleau et al., 2022). Specifically, DI corresponds to the application of water at lower amounts than the potential evapotranspiration (ETc) of vines. Williams et al. (2010) studied the response of vines under Mediterranean conditions to different irrigation inputs ranging between 20% and 140% of ETc and observed maximum yields and berry weights when 60% and 80% of ETc were applied; this means that water applied lower than 4000 m^3 ha^{-1} and greater than 8000 m^3 ha^{-1} did not guarantee the best berry weight, yield or cluster number. Other studies have reported that simple reductions in the irrigation threshold in terms of ETc (70% and 80%) or irrigation arrest 13–21 days before harvest saved considerable amounts of water, varying between a minimum of 300 m^3 ha^{-1} in Brazil (Conceição et al., 2014) and a maximum of 2400–

3000 m^3 ha^{-1} per season in Spain (Conesa et al., 2015). In contrast, an excessive reduction in water application can result in severe losses of grape yield and quality, and excessive irrigation suppresses the advantages of using this strategy by increasing vigour (Jones, 2004).

Measurements of climatic factors and soil water content are both practical and increasingly available for wine grape producers to estimate wine grape water requirements (Evett et al., 2012). The average values of evapotranspiration in grapevines (ETc) can range between 2.2 and 5.6 mm day^{-1}. This variation in ETc mainly derives from differences in environmental conditions (e.g. evaporative demand, soil type) and crop characteristics (e.g. genotype, canopy architecture) or agronomic strategies (e.g. trellis system, use of covering plastic/netting, weed control, planting density) in the different regions, which influences the ground cover fraction and, consequently, soil water loss (Permanhani et al., 2016).

The central zone of Chile has seen great development in wine grape production, particularly in the central valley of the Maule region, where the soils are loam and clay loam (Hadarits et al., 2016). There are approximately 52,000 ha of grape vine production in the region, supplying 41% of the total surface area for wine production in Chile (ODEPA, 2021). However, the region receives a rather limited average annual rainfall of approximately 656 mm, with a dry period of 7 months (Santibañez et al., 2017). Most of the vineyards in the Maule region are irrigated by either furrow or drip systems. Future precipitation is uncertain, and the frequency and magnitude of processes such as the El Niño–Southern Oscillation (ENSO) may change, causing more climate variability (Cai et al., 2021). Less rainfall in fall would be beneficial for producers, as the risk of botrytis would diminish, but less precipitation in winter compromises the soil water recharge cycle, resulting in reduced water supplies for irrigation. The practices adopted by farmers to cope with drought include night irrigation and decreasing irrigation frequency as the growing season progresses.

Therefore, it is important to evaluate the potential water savings in vineyards in the Maule region, where a comprehensive assessment of soil water balance in the field should offer tools and information to guide future irrigation practices and ensure the productivity and sustainability of wine grape production in the region. We hypothesize that it is possible to reduce the irrigation water supply in a commercial vineyard (Cabernet Sauvignon) in the Maule region without causing yield damage as a strategy to achieve improved WUE and reduced irrigation costs. A site-specific assessment of soil water balance is key to allowing winegrowers to develop appropriate irrigation practices in commercial vineyards. The main aim of this study was to evaluate the potential savings of irrigation water by assessing the soil water balance during a typical vine growing season in a commercial varietal bulk wine vineyard in the Maule region, Chile. This study provides insights into the influences of different irrigation water applications on soil water status and its potential effects on grape yields, WUE and the cost of irrigation to help improve irrigation practices in the region and other similar regions under Mediterranean climatic conditions.

2 | MATERIALS AND METHODS

2.1 | Field experimental site

The field trial was established in a large commercial vineyard located at Sagrada Familia (35°03′05.1″ S, 71°20′03.7″ W), Curicó province, Maule region, Chile, during the grape growing season of 2017–2018. The rooted vines of *Vitis vinifera* L. (Cabernet Sauvignon) were planted in 2001 and spaced 3 × 2 m (1666 vines ha^{-1}) in a plot of 10.45 ha. The historical average grape yield for this site is approximately 25,000 kg ha^{-1}, which is aimed at the production and export of varietal bulk wine. The vineyard is irrigated using a single-line drip irrigation system located next to the vine trunks, which is tied to the soil of the vineyard ridge. The drip line has 4-L h^{-1} inline emitters spaced at a distance of 1 m (two drippers per vine). Vines are trained on an east–west-oriented overhead trellis system. According to Natural Resources Information Centre (CIREN, 1997), the soils belong to the Santa Rosa de Lontué soil series (loam, fine, mixed, thermic of the Fluventic Haploxerolls), which is a sedimentary deep alluvial soil that is nearly level and has poor drainage conditions. The textural soil class is loam to sandy clay loam. The climate in the study area is a warm-summer Mediterranean climate (Csb) with a mean annual precipitation of 656 mm, of which approximately 7 months are dry (between October and April) (Santibañez et al., 2017). The mean temperature for the growing season of the vineyard (September to March) is 19°C. Pest management, canopy management, pruning and fertilization (by fertigation) in the vineyard were applied according to the standard local agricultural practices for commercial vineyards.

2.2 | Treatments and experimental design

The irrigation treatments consisted of the application of three different irrigation rates. For this purpose, the T_1 and T_2 irrigation drippers were replaced by other irrigation drippers with lower flow rates (Table 1). The

irrigated treatment T_0 represents the control and current irrigation treatments of the vineyard with a dripper flow of 4 L h^{-1}. Treatment T_1 was an adjustment of the current irrigation management method, which reduced the amount of irrigated water to 75% by replacing the dripper flow to 3 L h^{-1}. Finally, treatment T_2 was reduced to 50% of the amount of irrigated water applied by replacing the dripper flow to 2 L h^{-1}.

A discharge rate test was carried out in the field over 54 drippers (six drippers per treatment in every block) by measuring the volume of water discharged to a container for 1 min.

The irrigation treatments were applied from 24 October 2017 to 24 April 2018. All vines received the same irrigation timing and with the same regularity. The frequency of irrigation was once or twice per week (depending on the availability of irrigation water in the vineyard).

The experiment had a complete randomized block design with three treatments and three replications (Figure 1). The treatments were carried out over three rows of seven consecutive plants (two border vines). Consequently, each experimental unit consisted of five vines, replicated three times, in an area of 126 m^2 for a total of 45 vines.

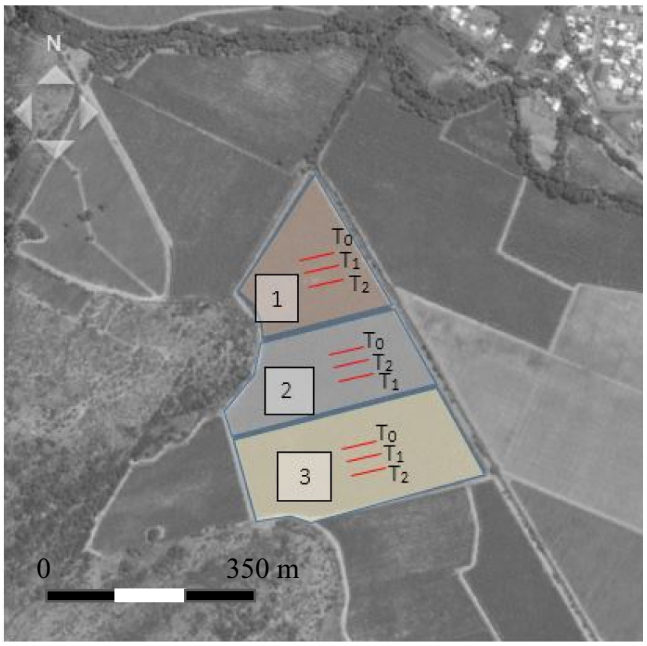

FIGURE 1 Layout of experimental field trials. The three operating irrigation blocks were each 126 m^2 in a plot of 10.4 ha of Cabernet Sauvignon commercial vines, Sagrada Familia, Maule region, Chile. Irrigation treatment T_0 corresponds to current irrigation volumes, T_1 corresponds to 75% of current irrigation volumes, and T_2 corresponds to 50% of current irrigation volumes.

2.3 | Calculation of evapotranspiration (ETc)

The reference evapotranspiration (ETo) was obtained using the Penman–Monteith equation online from an automatic weather station (A730; Adcon Telemetry, Austria) installed in Panguilemu (35°22′15″ S, 71°35′50″ W) above a grass cover within 8 km of the experimental site. The vineyard evapotranspiration (ETc) (mm day^{-1}) was calculated using Equation (1) as follows:

$$\mathrm{ETc} = \mathrm{ETo} \times K_c, \quad (1)$$

where K_c is the single crop coefficient. The K_c values reported in the literature are not adapted to the local conditions. As there are differences in K_c-validated values in vineyards due to the structure of the grapevine canopy (Ortega et al., 2005; Ortega-Farías et al., 2017), a suitable K_c value was searched to calculate the ETc of vines in the study fields (Table 2). Several studies have noted that the K_c of vines is linearly related to canopy cover (Figure 2) due to the structure of the vines (Allen et al., 1998; Ortega-Farías et al., 2017; Williams & Ayars, 2005). In an overhead trellis system, the interception of light increases in comparison to a vineyard conducted as a vertical curtain. The *Food and Agriculture Organization Irrigation and Drainage Paper No. 56* (FAO-56) (Allen et al., 1998) recommends K_c values of 0.3 for the initial, 0.85 for the mid-season and 0.45 for the late-season stages for table grapes growing at 2 m height from the floor (Table 2) and Pudney and Skewes (2004) from 0.3 from budburst (October) until flowering (November), 0.5 from flowering to veraison (December), 0.7 from fruit development until ripening (March) and 0.45 from fruit development until harvest (April) (Table 2).

The single crop coefficients used to calculate ETc in this study were similar to those previously used by Ortega-Farías et al. (2017) for Cabernet Sauvignon and Merlot trained on overhead trellis in the Molina valley, Maule region, Chile and are shown in Figure 2.

TABLE 1 Fully irrigated (T_0) and two reduced irrigation treatments (T_1 and T_2) in field study.

Treatment	% adjustment %	Dripper flow L h^{-1}	Number of emitters per plant	Dripper discharge mm h^{-1}
T_0	100	4	2	1.33
T_1	75	3	2	1.00
T_2	50	2	2	0.66

TABLE 2 Summary of crop coefficient (K_c) values for initial, mid-season and late-season stages for grapevines.

Crop coefficient (K_c) studies in grapevines	Season stages		
	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ late}$
Allen et al. (1998) (overhead trellis system)	0.30	0.85	0.45
Pudney and Skewes (2004)	0.30	0.70	0.45
Carrasco-Benavides et al. (2012) (vertical shoot system)	0.50	0.60	0.60
Ortega-Farías et al. (2017) (overhead trellis system)	0.30	0.80–0.90	-

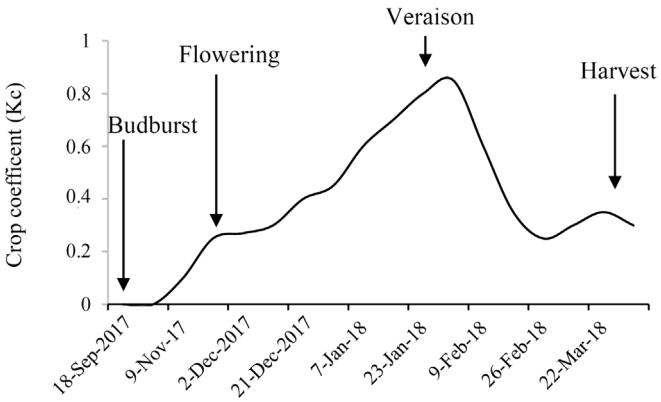

FIGURE 2 Single-crop coefficient estimation used for calculating evapotranspiration (ETc) for Cabernet Sauvignon commercial vines in Maule region, Chile. *Source*: Modified from Wample and Smithyman (2002) and adapted from Ortega-Farías et al. (2017).

2.4 | Soil hydraulic properties

Soil samples were collected to determine the physical and hydrological characteristics of the soil, the rooting depth of the vine and the soil profile morphological descriptions in the study field. Three soil samples were collected from each soil layer until the rooting depth was observed. In addition, three more soil samples per block were taken with a soil auger at the beginning of the growing season (Table 3).

The collected soil samples were analysed in the soil Physics Laboratory of the Faculty of Agricultural Sciences at the University of Chile. The samples were assessed for their soil texture class by the Bouyoucos method, bulk density (BD) by the cylinder method, organic matter by the calcination method, and field capacity (FC) and permanent wilting point (PWP) by using pressure devices at 33, 100 and 1500 kPa, as described by Sandoval et al. (2011). The plant-available soil water storage is defined as the difference between the FC and PWP (water retained at pore water pressures of −33 and −1500 kPa, respectively), and it was calculated for each block.

TABLE 3 Summary of key parameters and frequency and methods of their measurement in study field.

Parameter measurement	Frequency	Method
Evapotranspiration	Weekly (all the growing season)	Weather data used for Penman–Monteith equation (Allen et al., 1998)
Soil hydraulic properties	Once (beginning of the season)	Pressure devices, soil laboratory
Soil moisture	Hourly	Soil moisture sensors Decagon GS3
Water table level	Fortnightly (all the growing season)	Piezometer at 150 cm
Timing irrigation	Eventwise	Register time and rate of irrigation
Canopy cover	Fortnightly	Canopeo application
Yield	Once at harvest	Weight in field of fresh fruit
Total soluble solids (°Brix)	Once at harvest	Digital refractometer
Density	Once at harvest	Portable density meter
pH	Once at harvest	Potentiometer
Total acidity	Once at harvest	g L^{-1} of sulphuric acid

2.5 | Soil water measurements

A set of frequency domain reflectometry (FDR) (GS1 and GS3 by Decagon) instruments were installed to monitor hourly variations in volumetric water content (θ_v, $m^3\ m^{-3}$), temperature (°C) and electrical conductivity (mS cm^{-1}) in the soil profile. The θ_v of GS1 was determined by measuring the dielectric constant of the medium using capacitance and frequency domain technology (Decagon Devices, Inc.). The GS3 sensor

monitored the bulk electrical conductivity (EC), in addition to θ_v and soil temperature (Decagon Devices Inc.). An EM50 data logger was used to receive and store the soil water content measurements. The EM50 is a five-port self-contained data logger that is especially suitable for field research and commercial agriculture. These devices were housed in a weather-resistant enclosure, making them suitable for long-term outdoor operation (Decagon Devices, Inc.).

Three GS3 sensors per block were installed under the emitter of three vines, which were randomly selected. The data collected were stored every hour in a data logger (EM50 by Decagon), which stored the raw data for each sensor. The installation of each sensor was performed accurately to ensure that gaps around the probe did not provide preferential water pathways for irrigation water to penetrate more easily into the soil than in the surrounding area and that stones in the soil did not cause disturbance to the readings obtained. They were installed vertically from the soil surface, directly under the drip line. The root zone extended to a depth of 90 cm, and the active root zone extended from 10 to 50 cm. The GS1 sensor was placed at 150 cm (Figure 3), and the water content of the deepest layer of the soil profile was measured for each treatment. The GS3 sensor was installed at 50 cm (Figure 3) and measured the soil water content, temperature and electrical conductivity at the root zone in each row. The data obtained from each of the sensors were stored in a data logger and downloaded fortnightly (Table 3) when the notebook was directly connected to the sensor in the field.

The soil moisture sensors (GS3 and GS1 Decagon) were field evaluated to ensure accurate soil water readings. Two soil samples were taken at the same depth (50 cm) in the three replications at different times and analysed in the laboratory by measuring their gravimetric soil water content. The water content of the soil was determined by weighing the sample before and after drying at 105°C for 24 h in the laboratory. The samples were taken on 22 April 2018, after a long dry period of 20 days and 12 May 2018, after a recent irrigation event.

Three piezometers made of open-ended pipes of 50 mm PVC, grooved and coated with nylon mesh, were placed in the soil profile in each block to a depth of 1.5 m to measure the contribution of shallow groundwater to the soil water balance. These were set in the same location as the Sensor GS1 (see Figure 3). The depth to groundwater in the piezometers was measured fortnightly (Table 3) using manual recording, and the readings were used to calculate the plant groundwater use during the vine growing season.

2.6 | Plant growth parameters, canopy cover, grape yield and quality parameters

The total canopy cover of each experimental vine was estimated fortnightly throughout the entire growth season by the Canopeo MATLAB (iOS) App (Oklahoma State University, http://www.canopeoapp.com) to quantify the percentage of canopy cover of live green vegetation (Patrignani & Ochsner, 2015). The Canopeo App was downloaded onto an iPhone. The app accesses the camera on the mobile device to estimate the green canopy cover (GCC) value (%). The images were taken by holding the iPhone on upwards-facing photos, parallel to the ground, by a single user, from shoulder height (150 cm) standing upright on top of the ridge between the plants

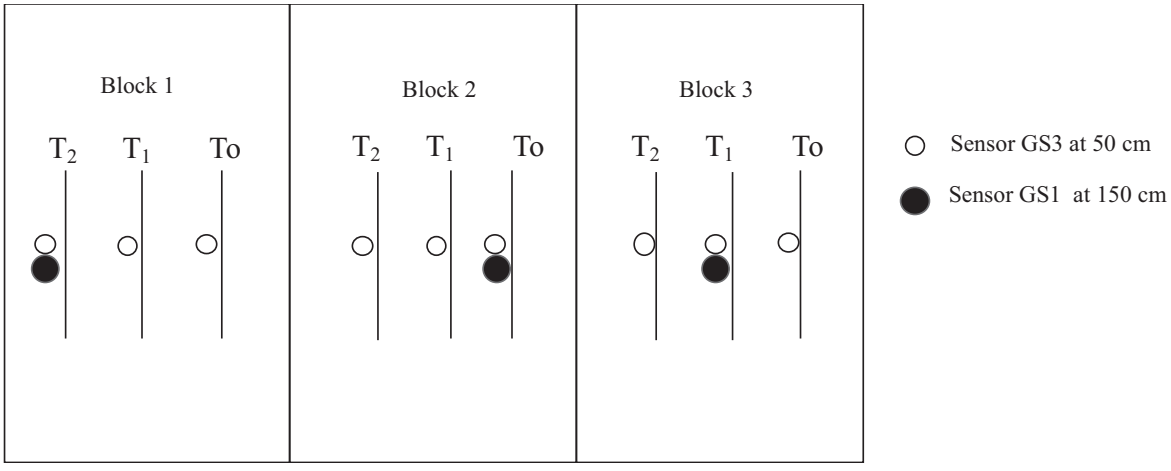

FIGURE 3 Placement of soil moisture sensors on treatments per block. Soil water sensors (GS3 and GS1 Decagon) were installed at two different soil depths: 50 cm (one per irrigation treatment and per replication) and 150 cm in one plant per treatment at experimental site. Piezometers were set in same location as Sensor GS1.

and pressing OK on the screen to obtain the GCC estimation. This process was repeated for each of the 45 plants in the trial between 11:00 AM and 2:00 PM, each 15 days, from 7 November 2017, to 12 April 2018.

The grape harvest was carried out from 19 April to 23 April 2018, at the end of the growing season. Hand harvesting was carried out on the experimental vines, separately per treatment and for each of the three replicates. All the clusters collected from each of the five centre vines were weighed per block to calculate the total grape yield (fresh fruit weight) of each treatment, which was then converted into kg ha^{-1}.

At the grape harvest, in all vines (five per treatment, replicated three times), three productive quality parameters were determined: total soluble solids (TSS), density, pH and total acidity. These parameters were measured from the juice of the sample of 200 berries collected at harvest from randomized clusters, per block and treatment. TSS were measured using a digital refractometer (Hanna Instruments Model HI 96811), the density was measured using a portable density meter (Anton Paar DMA 35), and the pH and total acidity were measured using a benchtop pH/ORP meter (Hanna Instruments Model HI 2222).

2.7 | Performance measures for irrigation

Irrigation water was supplied to all the experimental vines through a drip irrigation system, where the irrigation regime was currently chosen by the vineyard field manager. They sought to maintain soil water content above a chosen refill point, which they set subjectively when investigating a pit excavated for this irrigation purpose. The system was hand operated by a worker of the vineyard, as a current management, who individually opened and closed the irrigation pipe valves corresponding to each block, according to the schedule decided by the vineyard field manager. Typically, irrigation was turned on every 7–8 days for approximately 6–12 h. The date and timing of each irrigation event were recorded, and the total volume of applied irrigation water was quantified at the end of the season. Dripper discharge was tested once per season (2 February 2018) to verify that the quantities of water applied were as previously defined.

The observed grape yield and the amount of irrigation water applied were used to quantify the water use efficiency (WUE) at the end of the trial via Equation (2):

$$\mathrm{WUE} = \frac{\text{Grape Yield}}{\mathrm{WA}}, \tag{2}$$

where the grape yield refers to the annual grape (fresh fruit) yield (kg ha^{-1} $year^{-1}$) obtained at harvest and WA refers to the amount of water applied by irrigation (m^3 ha^{-1} $year^{-1}$).

The collected irrigation data were further analysed to estimate the cost of irrigation for different irrigation treatments. The operating costs included in the analysis are mainly those associated with the consumption of power (electricity) for pumping irrigation water and operating the irrigation system. In this economic analysis, it was assumed that there was no cost for the water itself. The power required for pumping was calculated using Equation (3) as follows:

$$P = \frac{Q \times H}{0.102 \times \mathrm{Ef_p}}, \tag{3}$$

where P is the pump power (HP) required to irrigate the area, Q is the flow rate required (m^3 s^{-1}), H is the head required (m), and $\mathrm{Ef_p}$ is the estimated efficiency of the pumping, which in this case was assumed to be 70% (Antúnez et al., 2009).

The cost of irrigation water pumping was calculated per treatment at the end of the season using Equation (4) as follows:

$$\mathrm{CWP} = 0.745P\frac{\text{Cost US\$}}{\mathrm{KWh}} \times \mathrm{IT}, \tag{4}$$

where CWP is the cost of irrigation water pumping (US $), P is the power required (HP), and IT is the irrigation timing (hours). The cost-effectiveness of irrigation water use reduction (US$) was calculated by comparing the current irrigation of the vineyard (T_0) with that of the reduced irrigation treatments (T_1 and T_2) (Table 1).

2.8 | Statistical analysis

The grape yield data were analysed by performing a one-way analysis of variance (ANOVA) with the irrigation treatment as the fixed variable. The F test in the ANOVA table tests whether there are any significant differences among the grape yield means. Differences within treatments were analysed, and p values <0.05 were considered to indicate statistical significance.

The daily data obtained from the soil moisture data loggers were processed with the ECH2O utility and are presented in a descriptive way. The soil water balance of the trial was analysed, and graphics were generated for the 2017/2018 growing season.

3 | RESULTS AND DISCUSSION

3.1 | Soil physical and hydraulic properties

The soil textural class ranged from clay loam in topsoil to coarse-textured in depth (sandy clay loam and sandy loam). The soil organic matter (SOM) content on the soil surface was 3.7%, which was mainly associated with the incorporation of organic matter from different sources into the soil surface. During spring, the weeds were left to grow between rows, and in winter, pruned vine shoots were chipped and incorporated into the soil with the remaining vegetation.

As expected, SOM content slightly decreased with soil depth (Table 4). Although the soil BD increased with depth in the soil profile (Table 4), the surface layers had relatively greater BD values (from 1.47 to 1.38), which we attributed to compaction caused by machinery traffic. In this case, the high BD value in the first 30 cm is an indicator of soil compaction, hence increasing losses by surface runoff.

The plant-available soil water storage depends on the clay content (%) and SOM (%) and is greater at 0–30 cm depth and decreases with increasing soil depth. However, compacted clay horizons in the root zone provide less available water and a poor environment for root growth.

3.2 | Testing of soil moisture sensors

The soil sensors were field tested using data from GS3, which was located at a 50 cm depth in the soil profile. A strong relationship (coefficient of determination [R^2] = 0.74) was found between the measured volumetric soil water content (VWC) and the sensor VWC outputs (Figure 4) over a broad range of soil water content values (0.20–0.40 $m^3\ m^{-3}$), similar to the range of soil water data recorded during the trial. This strong linear association verified that soil moisture sensor readings could be compared and analysed across different experimental treatments.

It is important to note that the sensors tended to slightly overestimate the soil water content based on the calibration; however, they are consistent for comparing the effects of different irrigation treatments and practically aid irrigation scheduling in the field.

3.3 | Crop water requirements and irrigation amounts applied

A total of 26 irrigation events were recorded for each treatment from 11 November 2017 until 1 April 2018. The irrigation frequency for the trial was weekly (see details in Table 5), as is the current management of the vineyard. The total maximum water applied for

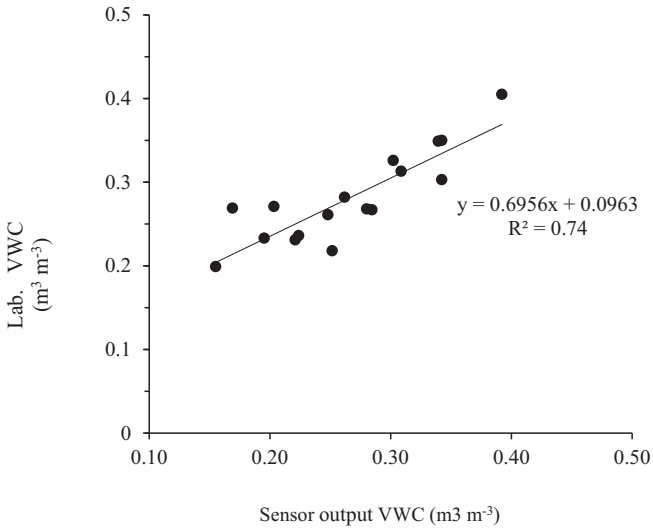

FIGURE 4 Soil moisture sensor calibration data (Decagon GS3) at 50 cm at different soil water content. VWC, volumetric soil water content.

TABLE 4 Physical properties of studied soil in Sagrada Familia, Maule region, Chile.

		Soil properties									
Horizon	Depth cm	Textural class	Clay %	Silt	Sand	SOM	BD Mg m^{-3}	Θ 33 kPa % vol	Θ 100 kPa	Θ 1500 KPa	PAW
Ap	0–30	Clay loam	29	30	41	3.7	1.47	33	22	18	15
B1	30–50	Clay loam	29	31	40	3.5	1.33	26	21	18	8
B2	50–80	Sandy clay loam	24	21	55	3.1	1.68	24	19	17	7
C1	80–90	Sandy loam	18	10	72	3.0	1.62	25	18	17	8
C2	90+	Sandy clay loam	26	26	48	-	1.62	30	26	18	12

Abbreviations: BD, bulk density; PAW, plant-available soil water; SOM, soil organic matter; Θ, volumetric water content.

the season was 341 mm in T_0, followed by 256 mm in T_1, and the lowest amount was 171 mm in T_2 (Table 5).

During the experiment (24 October 2017 to 24 April 2018), the ETc and rainfall in the growing season were 320 and 45 mm, respectively (Figure 5). Only three events of effective rainfall (more than 5 mm) occurred: one in November (8.8 mm) and the second and third in April (18.4 and 11.4 mm, respectively). The normal rainfall amount in the region is 99 mm between November and April (Santibañez et al., 2017); therefore, there was a rainfall deficit of 55% related to the impact of the megadrought that affected central Chile between 2010 and 2018 (Garreaud et al., 2019). The daily ETc value was calculated at a maximum of 5.5 mm per day on 6 January.

The vineyard manager assumed the availability of sufficient soil water stored in the rootzone in spring (September 2017) and the effective contribution of the shallow groundwater. Hence, no irrigation was applied in the vineyard during October 2017. However, since November 2017, the vineyard manager decides the amount of irrigation that should be applied to achieve the specific objective of high-yield production, that is, weekly irrigation for 12 h each to meet the crop water demand.

In treatment T_0, the total volume applied in the vineyard in 2017/2018 (342 mm in 26 irrigation events) was less than that in 2016/2017 (562 mm in 30 irrigations), while in 2016/2017, the irrigation started earlier (20 October 2016) in the same plot (personal communication of the vineyard manager). This difference is mainly explained by the soil water content in spring caused by the winter rainfall (565 mm in the winter of 2017 and 418 mm in the winter of 2016), as evidenced by the water logged in August 2017. Most of the time, the irrigation volume applied in this study was greater than 100% of the ETc for T_0 and greater than that reported by other authors in the region (Acevedo-Opazo et al., 2010, 2013; Ferreyra et al., 2004; Ortega et al., 2005); however, T_0 was under DI when ETc > water supplied during January and February (Figure 5). In addition, there is large variability even within the same region due to differences in interannual water availability. The sum of the irrigation applied and the rainfall received during the season was equivalent to 121% ETc, 94% ETc and 68% ETc for T_0, T_1 and T_2, respectively.

TABLE 5 Monthly interval (number of days = d), timing (hour = h) and amount of irrigation water supplied (mm) under three different irrigation treatments in 2017/2018 growing season at experimental site. Values are means of monthly irrigation amounts ± SD.

Time period	Interval days	Average irrigation time hours	T_0	T_1	T_2
			mm		
November	7	12	32 ± 0	24 ± 0	16 ± 0
December	7 ± 2	10 ± 3	59 ± 4	44 ± 3	29 ± 2
January	5 ± 2	11 ± 2	78 ± 2	59 ± 5	39 ± 3
February	6 ± 3	10 ± 3	77 ± 4	58 ± 3	39 ± 2
March	5 ± 2	11 ± 2	77 ± 3	58 ± 2	39 ± 2
April	9 ± 2	6 ± 5	18 ± 2	13 ± 2	9 ± 1
Annual total	6 ± 2	10 ± 3	341	256	171

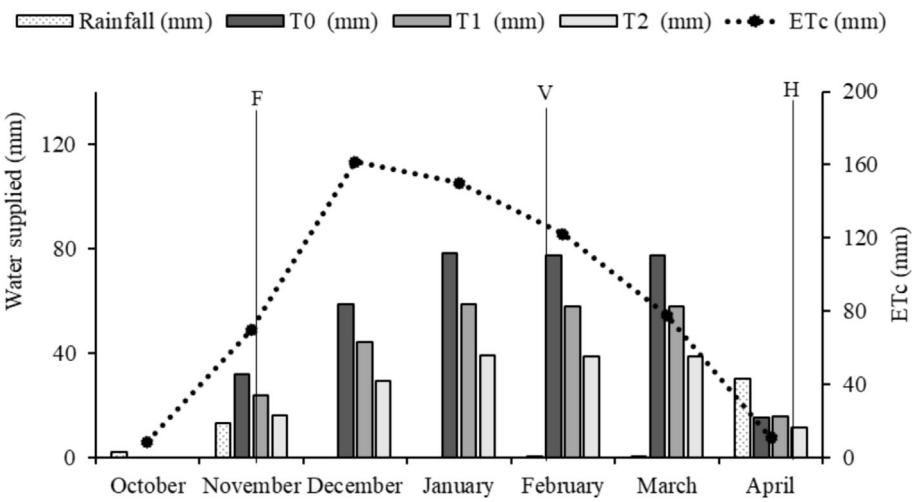

FIGURE 5 Monthly crop water requirements (ETc), rainfall received and irrigation water applied during 2017–2018 growing season for three treatments. Phenological stages: flowering (F), veraison (V) and harvest (H) of drip-irrigated Cabernet Sauvignon vineyard, Sagrada Familia, Maule region, Chile.

3.4 | Soil water dynamics

Piezometers placed below the rootzone (150 cm) detected the movement of the groundwater table at depth. It started at the beginning of the season at a shallow level and decreased during the season due to potential capillary rise and plant water uptake (Figure 6). In Block 1, the depth to shallow groundwater in spring (September to December) was measured at 40 cm below ground level (bgl), which increased to >120 cm bgl by the end of the season, whereas in Blocks 2 and 3, the depth to shallow groundwater in spring was measured at 80 and 110 cm blg in spring, respectively, and then followed the same tendency as in Block 1 (Figure 6). The initial differences in groundwater level among the three treatments may be related to the fact that Block 3 was closer to an open drainage ditch, which suggests that subsurface recharge affected this area. Considering that the bud break occurred around 23 September and the first irrigation occurred on 21 November, the vines used their water demand (at least 140 m^3 ha^{-1}) during that period from the stored soil water and shallow groundwater. This finding suggests that groundwater use was similar to that of Edwards and Clingeleffer (2013), who reported that up to 30% of the crop water requirement could be met from groundwater when the water table was 80 cm in Australia. This suggests that the contribution of shallow groundwater to the soil water balance of vineyards might be considered after winter for irrigation scheduling.

Irrigation was performed using an unfixed interval, not based on the measurement of soil water content from the sensors but from the winegrowers' observation of the soil profile in pits excavated. The irrigation time ranged between 6 and 12 h per block.

Irrigation generally started at 8 AM, and 2 h later, the wetting front was detected by the sensor at 50 cm depth in T_0. The initial VWC was high (>40%) due to rainfall during the winter season (Figure 8). As shown in Figure 6, Block 1 in spring had saturated soil below 40 cm. The water stored in the soil at the start of the growing season contributed to the total water supply. Irrigation maintained the T_0 and T_1 soils above FC until the end of January 2018, whereas VWC declined below 0.3 m^3 m^{-3} in the top 0.5 m of the soil profile, as determined by the sensors (Figure 8).

However, a 50% reduction in irrigation T_2 (compared to T_0) maintained the VWC above the PWP, mostly closer to and above the FC of the soil (Figure 8). None of the treatments were likely to have been subjected to even a mild degree of water stress as even in the top 50 cm of soil, the lowest VWC was >0.20 m^3 m^{-3} at the end of the

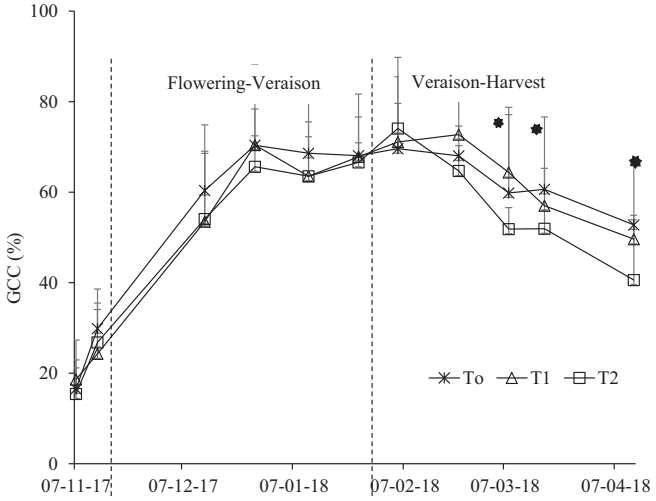

FIGURE 7 Percentage of green canopy cover (GCC) registered with Canopeo MATLAB (iOS) app. Each value is the mean of 15 central vines (five vines in three replicates). Bars denote SE. Asterisks indicate significant differences ($p < 0.05$) between irrigation treatments according to *F* test.

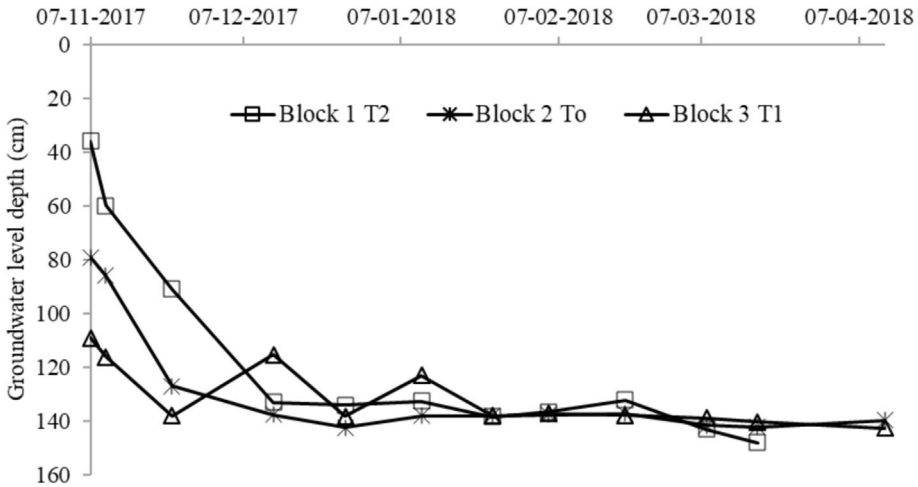

FIGURE 6 Depth to groundwater level (metres below ground level) during irrigation season in experimental plot, measured with piezometers. Sagrada Familia, Maule region.

season (Figure 8). Therefore, site-specific soil water balance assessments provide key information to guide irrigation applications to maintain appropriate levels of plant-available soil water in the soil profile. The consideration and management of water stored in the soil by the accumulation of rainfall in winter is crucial for adjusting irrigation to meet plant requirements in spring under Mediterranean conditions.

3.5 | Effect of irrigation treatments on vine growth and grape yield

The seasonal course of vine GCC development was similar among all irrigation treatments (Figure 7). A rapid increase in the canopy at the beginning of the season (Figure 7) resulted in maximal GCC values at the end of December 2017. These findings are consistent with the results of Munitz et al. (2017), who reported that the main period of vegetative growth occurs from flowering to veraison. The irrigation treatments did not affect plant growth, as measured by the GCC, from flowering until 8 March 2018 (at the end of the season), since when irrigation treatments had an effect on the GCC values, the GCC decreased in the order $T_0 > T_1 > T_2$. There were significant differences in the GCC measured between T_2 and T_1 during early March 2018 and April 2018 (Figure 7).

Regarding grape yield and quality parameters, the highest average yield was achieved in T_2; however, non-significant differences among treatments were obtained for grape yield, TSS, density, pH and total acidity at harvest (Table 6). The quality parameter values obtained were within the optimal range at harvest for all the treatments (TSS above 24 Brix in all treatments). However, it is known that high yields are commonly associated with reductions in grape quality since grape quality usually decreases in response to excess vigour, creating an imbalance between the reproductive and vegetative organs within plants (Medrano et al., 2015).

In another study, Ferreyra et al. (2004) reported that a water supply below 60% ETc significantly reduced the grape yield to 70% in Cabernet Sauvignon in the Maipo valley, Chile. According to Basile et al. (2011), applying water stress in some stages is disadvantageous: yield decreases, as do berry soluble solids, anthocyanins and polyphenols. However, the results of this study showed that the level of reduction in irrigation water applied was not enough to apply water stress to vines.

Even though all replications per treatment received the same amount of water, the vine in Block 1 had a lower yield (11% less than that in Block 2 and 9% less than that in Block 3) but had the highest TSS (Table 7). The lowest grape yield was obtained for the T_0 vines, in which the

TABLE 7 Average grape yield, water application and water use efficiency among irrigation treatments in irrigated vineyard of Cabernet Sauvignon.

Treatment	Average yield kg fresh grape ha^{-1}	Water applied m^3 ha^{-1}	WUE kg m^{-3}
T_0	18,932	3522	5.4
T_1	19,022	2642	6.5
T_2	19,503	1761	11.1

Abbreviation: WUE, water use efficiency.

TABLE 6 Grape yield and quality 'maturity' parameters per block and treatment of trial at harvest for Cabernet Sauvignon grapes under three irrigation treatments.

		Parameters				
Treatment		Yield kg ha^{-1}	TSS Brix	Density g cm^{-1}	pH	Total acidity g L^{-1}
Block 1	T_0	16,030 a	25.6 a	1.100 a	3.4 a	4.6 a
	T_1	18,994 a	24.5 a	1.096 a	3.4 a	3.8 a
	T_2	18,453 a	25.4 a	1.099 a	3.4 a	3.9 a
Block 2	T_0	20,607 a	25.1 a	1.098 a	3.5 a	3.5 a
	T_1	19.546 a	25.2 a	1.099 a	3.5 a	3.5 a
	T_2	20,265 a	24.4 a	1.096 a	3.4 a	3.4 a
Block 3	T_0	20,159 a	24.5 a	1.095 a	3.3 a	4.7 a
	T_1	18,526 a	25.0 a	1.097 a	3.3 a	4.0 a
	T_2	19,792 a	24.9 a	1.095 a	3.4 a	3.7 a

Note: Values followed by the same letter are not significantly different according to one-way analysis of variance with F test ($p \leq 0.05$).
Abbreviation: TSS, total soluble solids.

highest GCC was observed. Higher amounts of irrigation from the ETc may improve the vigour of plants and reduce grape yield at harvest, increasing the amount of water used.

3.6 | Calculation of WUE

The WUE, calculated as the ratio of the fresh grape fruit yield to the amount of irrigation water applied (Equation 2), increased by 20% and 100% in T_1 and T_2, respectively, compared to that in T_0 (current irrigation practices) in the study vineyard (Table 7). This increase in WUE resulted from the reduction (25%–50%) in water application and, in addition, no detrimental effects on plant-available water (Figure 8) or grape fresh yields (Table 7).

WUE was negatively correlated with the amount of water applied (WA) (Figure 9a). The wider dispersion of the WUE-yield data can be explained by the yield being affected not only by the amount of water but also by the soil characteristics (Figure 9b). However, this clearly suggested that T_0 (current irrigation practices) supplied excessive irrigation water, which did not increase grape yield. Grape yield was slightly greater in T_1 and T_2 than in T_0 (current irrigation practices) (Table 7). This could be attributed to the potential effects of excessive irrigation (current irrigation practices) on soil saturation, plant water uptake and nutrient availability in the soil profile.

3.7 | Potential savings in cost of irrigation

An economic analysis of the different amounts of irrigation water applied was performed considering the cost of

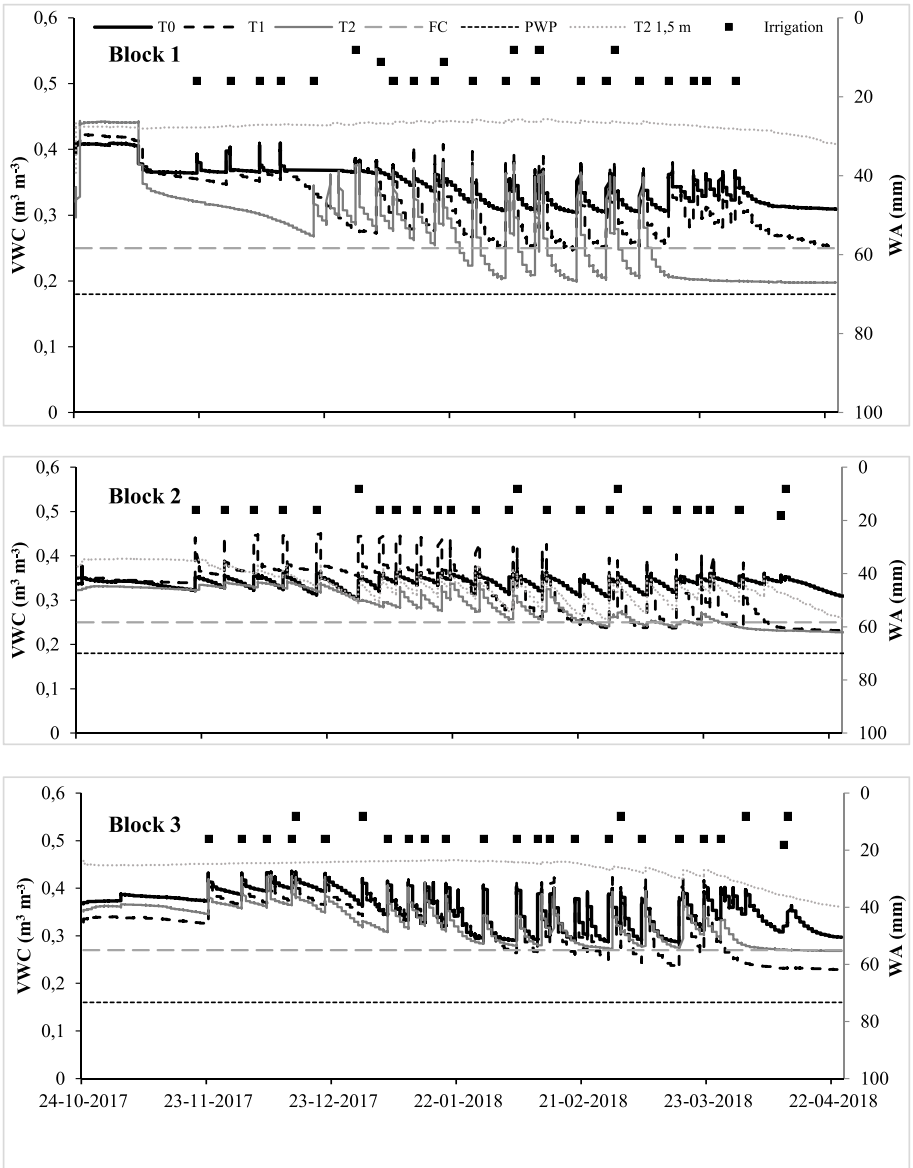

FIGURE 8 Hourly soil volumetric soil water content (VWC) measured for T_0, T_1 and T_2 at 50 cm and 1.5 m soil depths under the dripline of Blocks 1, 2 and 3 during growing season. Field capacity (FC) and permanent wilting point (PWP) were measured at laboratory for samples taken at 50 cm depth for each block. Dots are irrigations of water applied (WA) (mm).

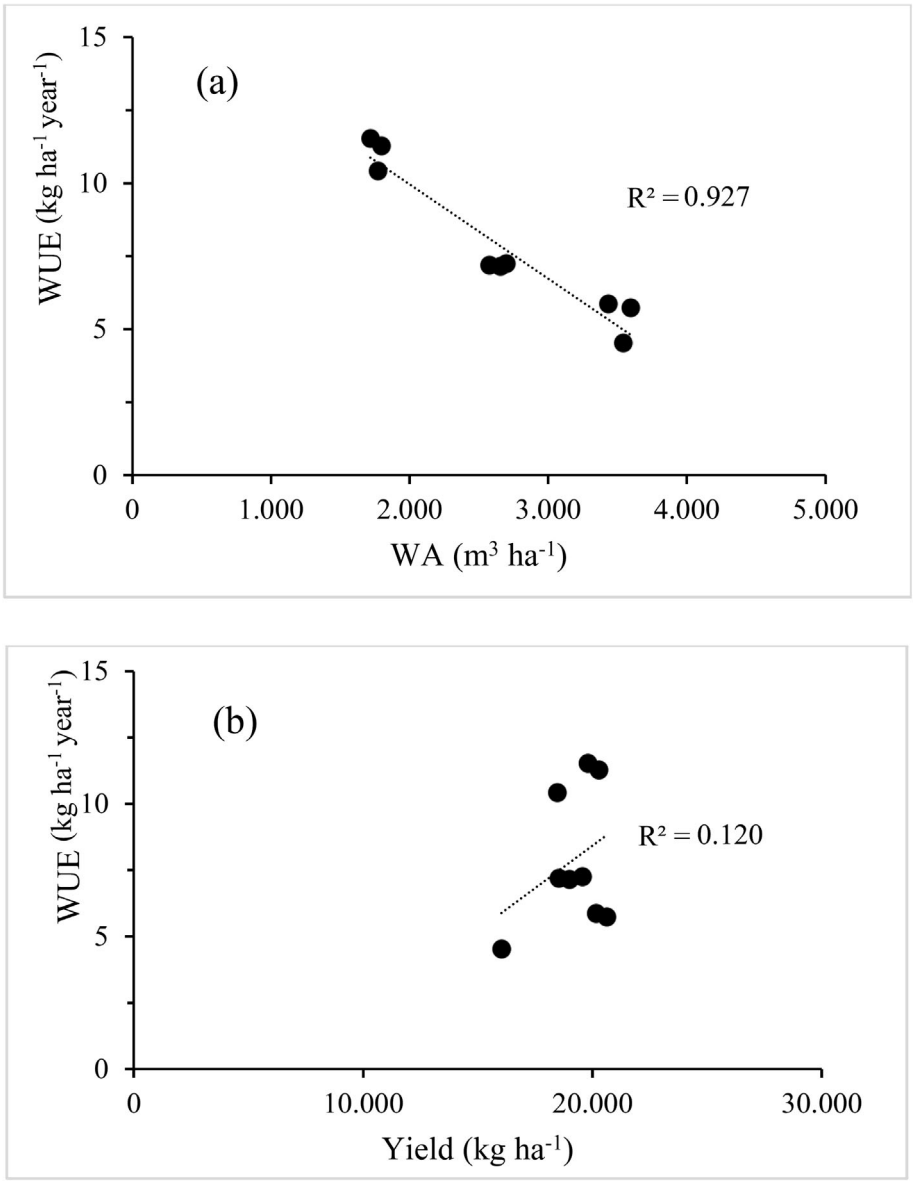

FIGURE 9 Relationships between water use efficiency (WUE) and water applied by irrigation (WA) and yield (kilograms of fresh grape). Lines represent linear trendlines.

TABLE 8 Cost of pumping irrigation water in one season and net return of Cabernet Sauvignon bulk wine production under different water irrigation treatments.

Irrigation reduction	Treatment	Total amount of water applied mm ha^{-1}	Power required KWh	Cost of pumping US$ ha^{-1}	Savings	US$ per 10.45 ha plot
0	T_0	341	8.6	405	-	4232
25%	T_1	256	6.5	304	100	3177
50%	T_2	171	4.3	203	202	2121

pumping as the only cost of operating irrigation at the vineyard. However, it is important to note that there are more irrigation costs, such as workforce, maintenance of equipment and other opportunity costs, associated with the allocation of the given supply of water to the local market. Table 8 summarizes the analysis of the water used per hectare and the potential savings calculated if the irrigation water applied in irrigation treatments T_1 (25% reduction) and T_2 (50% reduction) was reduced compared to that in T_0 (current irrigation) (Table 1).

A 50% reduction in irrigation amount could save approximately US$202 ha^{-1}, translating into potential savings of US$2112 for the 10.45 plot of the study vineyard. In addition, a reduction in power consumption for irrigation is expected to deliver other environmental benefits, for example, any indirect water consumption and climatic emissions associated with the power (electricity) supply in the study region.

4 | CONCLUSIONS

We found that it is possible to reduce the irrigation water supply in a commercial vineyard (Cabernet Sauvignon) in the Maule region by at least 50% of the current irrigation without causing any significant reduction in Cabernet Sauvignon yield. However, any potential savings in irrigation water must be considered carefully for its potential effects on groundwater recharge and flows at catchment/basin scales.

A reduction in the amount of excessive irrigation currently applied is expected to benefit local soil hydrology considering the shallow groundwater and poor drainage conditions at the study site. In addition, a 50% reduction in current irrigation could reduce the costs of irrigation by approximately US$202 per hectare of vineyard.

Based on the information derived from this study, potential savings in irrigation water can be realized by replacing the current dripper lines with those with less discharge to reduce the amount of irrigation applied according to the soil moisture status. Readily available soil moisture sensors could be deployed to calculate and apply appropriate levels of irrigation that match the soil water deficit with the irrigation rate.

The field experiment to improve irrigation management in a vineyard is site specific yet representative of a drip-irrigated vineyard in the Maule region, which was conducted in an over-trellis system of a Cabernet Sauvignon commercial vineyard in compacted soil with poor drainage conditions in winter.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Acevedo-Opazo, C., Ortega-Farías, S. & Fuentes, S. (2010) Effects of grapevine (*Vitis vinifera* L.) water status on water consumption, vegetative growth and grape quality: an irrigation scheduling application to achieve regulated deficit irrigation. *Agricultural Water Management*, 97(7), 956–964. Available from: https://doi.org/10.1016/j.agwat.2010.01.025

Acevedo-Opazo, C., Valdés-Gómez, H., Taylor, J.A., Avalo, A., Verdugo-Vásquez, N., Araya, M., et al. (2013) Assessment of an empirical spatial prediction model of vine water status for irrigation management in a grapevine field. *Agricultural Water Management*, 124, 58–68. Available from: https://doi.org/10.1016/j.agwat.2013.03.018

Allen, R., Pereira, L., Raes, D., et al. (1998) *Crop evapotranspiration. Guidelines for computing crop water requirements*. Rome, Italy: Food and Agriculture Organization of the United Nations.

Antúnez, A., Felmer, S., Mora, D. (2009) Eficiencia de riego en sistemas localizados Boletin INIA—Instituto de Investigaciones Agropecuarias. No. 190. San Fernando, Chile.

Azorín, P.R. & García, J.G. (2020) The productive, economic, and social efficiency of vineyards using combined drought-tolerant rootstocks and efficient low water volume deficit irrigation techniques under mediterranean semiarid conditions. *Sustainability*, 12(5), 1930. Available from: https://doi.org/10.3390/su12051930

Basile, B., Marsal, J., Mata, M., Vallverdú, X., Bellvert, J. & Girona, J. (2011) Phenological sensitivity of Cabernet Sauvignon to water stress: vine physiology and berry composition. *American Journal of Enology and Viticulture*, 62(4), 452–461. Available from: https://doi.org/10.5344/ajev.2011.11003

Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J.S., et al. (2021) Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment*, 2(9), 628–644. Available from: https://doi.org/10.1038/s43017-021-00199-z

Carrasco-Benavides, M., Ortega-Farías, S., Lagos, L.O., Kleissl, J., Morales, L., Poblete-Echeverría, C., et al. (2012) Crop coefficients and actual evapotranspiration of a drip-irrigated Merlot vineyard using multispectral satellite images. *Irrigation Science*, 30, 485–497. Available from: https://doi.org/10.1007/s00271-012-0379-4

Chapman, D.M., Roby, G., Ebeler, S.E., Guinard, J.X. & Matthews, M.A. (2005) Sensory attributes of Cabernet Sauvignon wines made from vines with different water status. *Australian Journal of Grape and Wine Research*, 11(3), 339–347. Available from: https://doi.org/10.1111/j.1755-0238.2005.tb00033.x

Cifre, J., Bota, J., Escalona, J.M., Medrano, H. & Flexas, J. (2005) Physiological tools for irrigation scheduling in grapevine (*Vitis*

vinifera L.). An open gate to improve water-use efficiency? *Agriculture, Ecosystems & Environment*, 106(2-3), 159–170. Available from: https://doi.org/10.1016/j.agee.2004.10.005

CIREN. (1997) *Estudio Agrológico VII Región. Descripciones de suelos, materiales y símbolos*. Publication N°117. Santiago, Chile: Natural Resources Information Centre (CIREN).

Conceição, M., Savini, T., de Souza, R., et al. (2014) Irrigation cutoff during ripening stage of Niagara Rosada grapes. In: *INOVAGRI international meeting 2. Fortaleza, Brazil. 2014*. Fortaleza, Brazil: Inovagri, pp. 2896–2901.

Conesa, M., de la Rosa, J., Artés-Hernández, F., Dodd, I.C., Domingo, R. & Pérez-Pastor, A. (2015) Long-term impact of deficit irrigation on the physical quality of berries in "Crimson Seedless" table grapes. *Journal of the Science of Food and Agriculture*, 95(12), 2510–2520. Available from: https://doi.org/10.1002/jsfa.6983

Edwards, E. & Clingeleffer, P. (2013) Interseasonal effects of regulated deficit irrigation on growth, yield, water use, berry composition and wine attributes of Cabernet Sauvignon grapevines. *Australian Journal of Grape and Wine Research*, 19(2), 261–276. Available from: https://doi.org/10.1111/ajgw.12027

Evett, S., Schwartz, R., Casanova, J. & Heng, L.K. (2012) Soil water sensing for water balance, ET and WUE. *Agricultural Water Management*, 104, 1–9. Available from: https://doi.org/10.1016/j.agwat.2011.12.002

Ferreyra, R., Selles, G.V., Peralta, J. & Valenzuela, J.B. (2004) Effect of water stress applied at different development periods of Cabernet Sauvignon grapevine on production and wine quality. *Acta Horticulturae*, 646, 27–33. Available from: https://doi.org/10.17660/ActaHortic.2004.646.2

Garreaud, R.D., Boisier, J.P., Rondanelli, R., Montecinos, A., Sepúlveda, H.H. & Veloso-Aguila, D. (2019) The Central Chile Mega Drought (2010–2018): a climate dynamics perspective. *International Journal of Climatology*, 40, 421–439. Available from: https://doi.org/10.1002/joc.6219

Hadarits, M., Santibañez, O. & Pittman, J. (2016) Drought risks and opportunities in the Chilean grape and wine industry: a case study of the Maule Region. In: Polo, H., Hurlbert, M. & Warren, J. (Eds.) *Vulnerability and adaptation to drought: the Canadian Prairies and South America*. Calgary: University of Calgary Press, pp. 303–326 https://doi.org/10.2307/j.ctv6gqwv1.16

Herath, I., Green, S., Singh, R., Horne, D., van der Zijpp, S. & Clothier, B. (2013) Water footprinting of agricultural products: a hydrological assessment for the water footprint of New Zealand's wines. *Journal of Cleaner Production*, 41, 232–243. Available from: https://doi.org/10.1016/j.jclepro.2012.10.024

Jones, H. (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany*, 55(407), 2427–2436. Available from: https://doi.org/10.1093/jxb/erh213

Keller, M. (2005) Deficit irrigation and vine mineral nutrition. *American Journal of Enology and Viticulture*, 56(3), 267–283. Available from: https://doi.org/10.5344/ajev.2005.56.3.267

Medrano, H., Tomás, M., Martorell, S., Escalona, J.M., Pou, A., Fuentes, S., et al. (2015) Improving water use efficiency of vineyards in semi-arid regions. A review. *Agronomy for Sustainable Development*, 35(2), 499–517. Available from: https://doi.org/10.1007/s13593-014-0280-z

Munitz, S., Netzer, Y. & Schwartz, A. (2017) Sustained and regulated deficit irrigation of field-grown Merlot grapevines. *Australian Journal of Grape and Wine Research*, 23(1), 87–94. Available from: https://doi.org/10.1111/ajgw.12241

Naulleau, A., Gary, C., Prévot, L., Vinatier, F. & Hossard, L. (2022) How can winegrowers adapt to climate change? A participatory modeling approach in southern France. *Agricultural Systems*, 203, 103514. Available from: https://doi.org/10.1016/j.agsy.2022.103514

ODEPA. (2021) Wine statistics. Oficina de Estudios y Políticas Agrarias (ODEPA). Available at: https://www.odepa.gob.cl/estadisticas-del-sector/estadisticas-productivas [Accessed 3rd August 2023].

Or, D., Wraith, J.M., Robinson, D.A., et al. (2012) Soil water content and water potential relationships. In: Huang, P.M., Li, Y. & Sumner, M.E. (Eds.) *Handbook of soil sciences, properties and processes*, 2nd edition. USA: CRC Press Taylor and Francis Group, pp. 1–28.

Ortega, S., Acevedo, C., Duarte, M., et al. (2005) Sistema de programación del riego de vides para mejorar la calidad de mostos y vino. In: *Serie Actas INIA No. 39. Seminario Internacional. Manejo del riego en vides para vino y mesa*. Santiago, Chile: Instituto de Investigaciones Agropecuarias (INIA), pp. 133–145.

Ortega-Farías, S., Fonseca, D., de la Fuente, D., Kilic, A., Ortega-Salazar, S., Allen, R., et al. (2017) Remote sensing model to evaluate the spatial variability of vineyard water requirements. *Acta Horticulturae*, 1188(1188), 235–242. Available from: https://doi.org/10.17660/ActaHortic.2017.1188.30

Patrignani, A. & Ochsner, T. (2015) Canopeo: a powerful new tool for measuring fractional. *Agronomy Journal*, 107(6), 2312–2320. Available from: https://doi.org/10.2134/agronj15.0150

Permanhani, M., Costa, J., Conceição, M., de Souza, R.T., Vasconcellos, M.A.S. & Chaves, M.M. (2016) Deficit irrigation in table grape: eco-physiological basis and potential use to save water and improve quality. *Theoretical and Experimental Plant Physiology*, 28(1), 85–108. Available from: https://doi.org/10.1007/s40626-016-0063-9

Pudney, N. & Skewes, M. (2004) Irrigation management. In: Nicholas, P. (Ed.) *Soil, irrigation and nutrition, grape production series*, Vol. Number 2. Adelaide: Hyde Park Press, pp. 148–173.

Rijsberman, F. (2006) Water scarcity: fact or fiction. *Agricultural Water Management*, 80(1-3), 5–22. Available from: https://doi.org/10.1016/j.agwat.2005.07.001

Sandoval, M., Dörner, J., Seguel, O., et al. (2011) *Métodos de análisis físico de suelos*. Chile: Sociedad Chilena de la Ciencia del Suelo.

Santibañez, F., Santibañez, P., Caroca, C., et al. (2017) *Atlas agroclimático de Chile: Estado actual y tendencias. Regiones Valparaíso, Metropolitana, O'Higgins y Maule*. Esc. 1: 1.200.000. Chile: Universidad de Chile.

Wample, R.L. & Smithyman, R. (2002) Regulated deficit irrigation as a water management strategy in Vitis vinifera production. FAO Deficit lrrigation Practices: Water Reports 22. Rome: FAO, pp. 89–100.

White, R. (2015) *Understanding vineyard soils*. 2nd edition. Oxford University Press, New York. https://doi.org/10.1093/oso/9780199342068.001.0001

Williams, L. & Ayars, J. (2005) Grapevine water use and the crop coefficient are linear functions of the shaded area measured

beneath the canopy. *Agricultural and Forest Meteorology*, 132(3-4), 201–211. Available from: https://doi.org/10.1016/j.agrformet.2005.07.010

Williams, L., Grimes, D. & Phene, C. (2010) The effects of applied water at various fractions of measured evapotranspiration on reproductive growth and water productivity of Thompson Seedless grapevines. *Irrigation Science*, 28(3), 233–243. Available from: https://doi.org/10.1007/s00271-009-0173-0

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