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# **New challenges for Uruguayan viticulture:** water management in the context of a changing climate

## **Nuevos desafíos para la viticultura uruguaya:** gestión del agua frente a un escenario de clima cambiante

## **Novos desafios para a viticultura uruguaia:** a gestão da água em um cenário de mudanças climáticas

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### Abstract

Climate scenarios in the medium and long term (2010-2070) foresee increased summer rainfall for Uruguay and the region, with increased water deficits and excess episodes. Although at the international level irrigation in viticulture has a long experience and tradition, at the local level (Uruguay), only 10% of the vineyard surface area implements a fixed or complementary system for water supply in their crops. This work aimed to model the crop water requirements for a vineyard in southern Uruguay based on pedo-climatic variables. In addition, the plant response to controlled deficit irrigation was evaluated in two consecutive seasons. The experiment was conducted in a 1.1 ha commercial vineyard in Canelones, Uruguay (34°36'S, 56°14W), during two successive seasons (2020-2021). The additional irrigation (I) treatment was compared against a control (C) without irrigation. A controlled water deficit was established from flowering to harvest. The adjustment in the demand was made as a function of a percentage of crop evapotranspiration. The Kc of the crop was estimated using digital tools. The simulation of the water balance made it possible to evaluate the vineyard water needs. Plants subjected to controlled deficit irrigation showed higher vegetative growth, positively impacting yield and the accumulation of sugars and anthocyanins in the berry. Based on our results, a supplementary water supply, at the right doses and time, allows us to face water deficit situations, positively impacting the productive and economic variables. Knowing the variability in a vineyard is necessary to achieve proper irrigation scheduling and optimize water use. New technologies applied to irrigation are an opportunity for winegrowers to obtain more sustainable vineyards and production.

**Keywords**: Tannat, irrigation, sustainability, site-specific management, water deficit

### Resumen

Los escenarios climáticos en el mediano y el largo plazo (2010-2070) prevén para el Uruguay y la región un aumento de las precipitaciones estivales, con aumento de episodios de déficits y excesos hídricos. Si bien a nivel internacional el riego en la viticultura presenta una amplia experiencia y tradición, a nivel local (Uruguay) solamente el 10% de la superficie de viñedos implementa de manera fija o complementaria alguna medida de aporte de agua en sus cultivos. El objetivo de este trabajo fue modelar a partir de variables pedoclimáticas las necesidades hídricas del cultivo para un viñedo en el sur del Uruguay. Además, en dos vendimias consecutivas se evaluó la respuesta de la planta al riego deficitario controlado.



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El experimento se realizó en un viñedo comercial de 1,1 ha ubicado en Canelones, Uruguay (34°36'S, 56°14W), durante dos temporadas consecutivas (2020-2021). El tratamiento con riego adicional (I) se comparó contra un testigo (C) sin riego. Se estableció un déficit hídrico controlado desde floración hasta cosecha. El ajuste en la demanda se realizó en función de un porcentaje de la evapotranspiración del cultivo. El Kc del cultivo fue estimado mediante herramientas digitales. La simulación del balance hídrico permitió evaluar las necesidades hídricas del viñedo. Las plantas sometidas a riego deficitario controlado presentaron un mayor crecimiento vegetativo que impactó positivamente en el rendimiento y la acumulación de azúcares y antocianos en la baya. Según nuestros resultados, un aporte suplementario de agua, en dosis y momentos justos, permite enfrentar situaciones de déficits hídricos con un impacto positivo en las variables productivas y económicas. Para lograr una adecuada programación del riego y optimizar el uso del agua es necesario conocer la variabilidad presente en un viñedo. Las nuevas tecnologías aplicadas al riego son una oportunidad que presenta el viticultor para lograr viñedos y producciones más sustentables.

**Palabras clave**: Tannat, riego, sostenibilidad, agricultura de precisión, déficit hídrico

**Resumo**

Os cenários climáticos a médio e longo prazo (2010-2070) prevêem um aumento da precipitação estival no Uruguai e na região, com um aumento dos episódios de déficit e excesso de água. Embora a nível internacional, a irrigação na viticultura tenha uma longa experiência e tradição, a nível local (Uruguai) apenas 10% da superfície da vinha implementa uma medida fixa ou complementar de fornecimento de água nas suas culturas. O objetivo deste trabalho foi modelar as necessidades hídricas das culturas para um vinhedo no sul do Uruguai com base em variáveis pedoclimáticas. Além disso, foi avaliada a resposta da planta à irrigação com déficit controlado em duas safras consecutivas. O experimento foi realizado em um vinhedo comercial de 1,1 ha localizado em Canelones, Uruguai (34°36'S, 56°14W), durante duas temporadas consecutivas (2020-2021). O tratamento com irrigação adicional (I) foi comparado com um controlo (C) sem irrigação. Foi estabelecido um déficit hídrico controlado desde a floração até à colheita. O ajuste no défice foi feito em função de uma percentagem da evapotranspiração da cultura. O Kc da cultura foi estimado através de ferramentas digitais. A simulação do balanço hídrico permitiu avaliar as necessidades hídricas da vinha. As plantas submetidas a uma irrigação deficitária controlada apresentaram um maior crescimento vegetativo, o que teve um impacto positivo no rendimento e na acumulação de açúcares e antocianinas no bago. Com base nos nossos resultados, um fornecimento suplementar de água, nas doses e momentos certos, permite-nos enfrentar situações de déficit hídrico com um impacto positivo nas variáveis produtivas e econômicas. Para conseguir uma programação adequada da rega e otimizar o uso da água, é necessário conhecer a variabilidade presente numa vinha. As novas tecnologias aplicadas à rega são uma oportunidade para os viticultores alcançarem vinhas e produções mais sustentáveis.

**Palavras-chave**: Tannat, irrigação, sustentabilidade, gestão específica do local, déficit hídrico

## 1. Introduction

*Vitis vinifera* L., the species to which most of today's cultivated vines belong, is centered on the Eurasian continent, where the climate is temperate and subtropical[1]. It is considered a drought-tolerant species[2]. Water demand during the growing season can range from 300 to 600 mm[3], even reaching 800 mm in warm weather conditions[4] in response to increased atmospheric demand. These volumes of water are not required equally throughout the crop cycle, varying according to the phenological stage (Eichhorn and Lorenz scale, EyL). It has been reported that frombud-break to bloom (4 to 19 EyL), water needs represent 9% of the total demand, while from bloom to veraison (19 to 35 EyL), the requirements increase to 41%[5]. In the period from veraison to harvest (35 to 38 EyL), 36% of the requirement is used, and finally, between harvest and leaf fall (38 to 47 EyL), the demand reaches the remaining 14%[5]. Although water requirements are low compared to other crops, under certain conditions, sub-optimal levels of this resource can be generated, causing water stress that conditions the growth and development of the crop.

The water status of the vineyard is one of the aspects that determine the product obtained, and, therefore, the type of wine to be produced. To determine the vineyard's water status, several techniques allow a direct or indirect estimation, being the basic leaf water potential ($\psi_b$) the most established and reported methodology[6-7]. The advantage of $\psi_b$ is that there are internationally validated reference thresholds (Table 1). These thresholds relate the water status to its impact on plant physiology[7] and the type of wine to be produced. To obtain high-quality red wines, it is necessary to start with excellent grape conditions, which is why it is recommended to follow a water strategy in 4 stages, depending on the phenology of the crop and the water requirements for each stage[8]. In the first stage, between bud-break and fruit set, it is recommended that the water availability of the plants should not be limited. At this stage, water is critical to ensure good leaf surface development and clusters formation for the next season[9-10]. In the second stage, a slight water deficit ($\psi_b$: -0.2 MPa to -0.4 MPa) is recommended between fruit set and veraison. Vegetative growth and early berry development are susceptible to water deficit[11-12]. Mild stress at this stage limits vegetative growth and defines yield potential due to an adjustment on cell volume[12]. In the third stage, between veraison and harvest, it is suggested that stress should be moderate ($\psi_b$: -0.4 MPa to -0.6 MPa). Moderate stress further limits vegetative growth and maintains active photosynthesis, favoring the accumulation of metabolites (sugars and anthocyanins) in the berry[7-8]. During the fourth stage, from harvest to leaf fall, the plants must be brought to a situation without a water deficit. During this period, the assimilates are translocated to the roots, trunks, and shoots[13], ensuring the necessary reserves for sprouting in the next crop cycle.

At present, Uruguay has an average annual rainfall of 1100 mm. However, the inter-annual variability of rainfall is high. Moreover, monthly rainfall distribution is not homogeneous throughout the years (0 mm to 300 mm per month), thus generating periods of water deficit or excess during the grape ripening period[14]. On the other hand, there is high variability in the soils of Uruguay[15] due to the diversity in the geological materials. The combination of climate and soil makes different vineyards more susceptible to water deficit situations. In addition, in the climate changecontext, a global reduction in precipitation is expected, with an increase in temperature and evapotranspiration[16]. Another phenomenon associated with climate change is the increase in the intensity, frequency, and duration of heat waves[17]. A heat wave is a succession of more than three days with abnormally high daily maximum air temperatures (greater than three times the standard deviation of the historical mean) for a given year[18-19]. Depending on the intensity and phenological stage, these extreme phenomena have an impact on fruit set[20], sugar and anthocyanin accumulation[21], smaller berries and lower quality[22]. For Uruguay and the region, in the medium and long term (2010-2080), an increase in rainfall is expected with an increase in extreme events (greater intra-annual variability), although springs would be drier[19]. This situation would be aggravated by ENSO (El Niño-Southern Oscillation) cycles, where Niña (or water deficit) years would be more severe in the south. In addition, the average temperature would increase between 1.5 and 3.0 °C, with an increase in the incidence of heat waves[19].

Based on the above, Uruguayan viticulture (and agriculture in general) will have to adapt to mitigate the climate change's effects. A controlled deficit irrigation strategy allows Uruguayan winegrowers to adapt to the new reality. The principle behind controlled deficit irrigation is to eliminate or reduce water inputs during specific periods to control vegetative vigor, andoptimize yield and grape composition[23]. This strategy is widely discussed in the literature[23-24], especially in arid or Mediterranean conditions. There are fewer reports of applying these techniques in sub-humid conditions or with soils with a high water storage capacity[25-28]. These types of soils and conditions are found in southern Uruguay, where the largest wine-growing area in the country is concentrated.

In Uruguay, only 10.8% of the vineyard area (635 ha) is irrigated[29], and this figure is on the rise as a response by winegrowers to a greater perception of climate change. Although the response is an increase in irrigation, the technical criteria for defining when and how much to irrigate are less clear. This work aimed to evaluate, through a climatic analysis of a 23-year historical series, the need for the implementation of controlled deficit irrigation under sub-humid conditions in a 1.1 ha vineyard in southern Uruguay. In addition, the impact of controlled deficit irrigation on vegetative growth, yield, grape and wine potential quality during two consecutive vintages was evaluated.

## 2. Materials and methods

### 2.1 Site and experimental design

The experiment was conducted in a 1.1 ha commercial vineyard in Canelones, Uruguay (34°36'S, 56°14W). The vineyard was planted in 1998 with *Vitis vinifera* L. cv. Tannat (clon 398), grafted on $SO_4$ rootstock. The distance between vines was 2.5 m × 1.2 m (3333 plants.ha$^{-1}$). The plants were pruned with a double guyot system, and the shoots were trained with the VSP (vertical shoot positioning) system. The vineyard was historically not irrigated and received nitrogen fertilization with urea, distributed half in pre-flowering and half in post-harvest. The total urea dose (46% N) was 140 kg per ha. This vineyard was selected because of its high variability in vine vigor from east to west. Ferrer and others[30] defined three vigor zones in this vineyard: high (HV), medium (MV), and low (LV). Vigor zones were determined using the normalized vegetation index (NDVI) during three consecutive seasons (2015, 2016, and 2017). The soil was classified as a vertic Arguidoll[31] based on the descriptions proposed by

FAO[32] and the USDA Soil Taxonomy classification[33]. Soil physical and chemical characteristics also showed a strong spatial variability, mainly in clay percentage, clay type, and total available water. The winegrower managed the two zones (HV/LV) in the same way. In all cases, weeds were controlled in the row with herbicides. The inter-row consisted of a mixture of grasses and *asteraceae*, with oats sown in autumn, controlled by periodic mowing (six times a year).

The field trial was conducted during the 2020 and 2021 seasons. Only the low vigor zone was selected because the water was identified as the main limiting factor in vigor expression[28]. Two treatments were established in this LV zone. A control treatment (C) followed the winegrower management (described above). The irrigation treatment (I) followed the criteria established for regulated deficit irrigation (RDI). To determine the irrigation doses, the climatic demand (ETo) was adjusted with the Kc of the crop. The Kc values of the crop were obtained weekly using the Williams and Ayars equation[34]. This equation relates the leaf area index (LAI) to the Kc of the crop. The determination of LAI is explained in section 2.3 (plant measurements). Once the adjusted climatic demand (ETc) was defined, irrigation water was applied according to the following criteria:

- From budding to flowering, 100% of the demand was applied.
- During flowering until harvest, 70% of the ETc was applied. The irrigation system was drip irrigation with a single irrigation tape. The drippers were spaced 40 cm apart and had a flow rate of 4 lt/h. Irrigation was carried out during morning hours.

Each treatment was arranged in a randomized block design with three replicates and 21 plants per replicate (63 plants per treatment).

### 2.2 Climate, soil and water balance

Meteorological data were collected from a weather station (34° 40' S, 56° 20' W, 10 km from the experimental site) managed according to WMO (World Meteorological Organisation) standards, belonging to INIA (National Agricultural Research Institute) "Las Brujas". Effective rainfall in the vineyard was recorded. The following meteorological variables were collected: accumulated rainfall during the crop cycle (September to March), reference evapotranspiration (Eto), maximum monthly air temperature (Tmax), minimum monthly air temperature (Tmin), and mean monthly air temperature (Tx).

In winter 2015, 168 soil samples were taken within the vineyard at two sampling depths (0-20, 20-40) using a grid design (10.8 m × 12.5 m) following the methodology proposed by Alliaume and others[35]. Organic matter (OM), % sand (Sa), % clay (Cl) and silt (Si) were determined in the samples taken at 0-20 and 20-40 cm. In addition, six soil auger inspections were carried out in each vigor zone to determine soil depth. With the soil analysis calculations and soil surveys, Total Available Water (TAW)[36] was calculated using the formulas proposed by Fernández[37], and Silva and others[38] for Uruguayan soils. The TAW estimated from soil texture and root depth was 180 mm with a predominance of montmorillonite (expansive clay) for the HV zone and less than 140 mm in the LV zone with higher illite content[39].

In order to analyze how climatic variability affects soil water availability for the crops and to verify if irrigation is necessary, a monthly water balance (WB) was calculated following the methodology proposed by Gaudin and Gary[40] for Mediterranean soils and without cover crop for the period 2000 to 2023. Model inputs were mean air temperature, effective precipitation, reference evapotranspiration, total available water, and Kc. The INIA climate database, vineyard rainfall, and TAW for each vigor zone (180 mm and 140 mm) were used. Monthly WB values were classified into five categories[41]. The criteria for each category were as follows:

1- **Very wet:** Rainfall above demand and TAW reconstituted.
2- **Wet:** Rainfall higher than demand and TAW not reconstituted (TAW of 99 to 90%).
3- **Sub-dry:** Rainfall less than demand and between 90 and 60% of TAW.
4- **Dry:** Rainfall less than demand and between 60 and 20% of TAW.
5- **Arid:** Rainfall less than demand and with less than 20% of the TAW.

Water supply during the trial years (2020 and 2021) is considered to be the sum of effective rainfall and irrigation. Rainfall, ETo and water balance are presented according to the following phenological periods: bud-break to flowering (BB: September and October), flowering to veraison (Bl: November to December), veraison (V: January) and harvest (H: November).

### 2.3 Plant measurements

<u>Leaf water status</u>: From bloom to harvest (19 to 38 EyL), vine water status was determined before sunrise ($\psi_b$) using a pressure chamber (SoilMoisture equipment, Santa Barbara, CA, USA). Ten evaluations were carried out in each year. Nine healthy,

expanded leaves were taken from each treatment (three leaves per replicate). With this information, the water stress integral or stress index (WSI) was calculated for each year and treatment. The WSI was calculated as the sum of all water potentials using the equation proposed by Myers[42], using the following equation:

$$\mathrm{SI} = \left| \sum_{i=0}^{i=t} \left( \Psi\mathrm{p}_{(i,i+1)} - C \right) * n \right| \quad Eq.1$$

Where:

$\Psi p_{(i+i+1)}$ is the measure of Ψp for each interval *i, i + 1*

*C* is the maximum Ψp reached for each year and condition, and *n* is the number of days in the interval.

The stress index is expressed in absolute values (MPa.day). Higher WSI values correspond to a higher water deficit. The interpretation of $\psi_b$ values and the impact on the plant were related to the thresholds established in the literature[6-7] as presented in Table 1.

**Table 1.** Threshold values of water deficit and their impact on plant response

| Water status ($\psi_b$, MPa) | Water stress level | Vegetative growth | Berry growth | Photosynthesis | Grape ripening |
|---|---|---|---|---|---|
| **0 to -0.2** | Absent | Normal | Normal | Normal | Normal |
| **-0.2 to -0.4** | Low to moderate | Reduced | Normal to reduced | Normal to reduced | Normal to stimulated |
| **-0.4 to -0.6** | Moderateto severe | Reducedto inhibited | Reducedto inhibited | Reducedto inhibited | Reducedto inhibited |
| **> -0.6** | Severe | Inhibited | Inhibited | Partial or total inhibition | Partial or total inhibition |

Adapted from Bernard and others[43]

Vegetative growth: Vegetative growth was assessed weekly from bud-break to veraison. Leaf area index (LAI) was estimated from images taken with a smartphone and processed with the application (App) VitiCanopy[44]. Six plants per replicate were evaluated and images were obtained using the front camera of the smartphone from under the plant at 80 cm between the plant and the device. In addition, 10 representative shoots (similar shoots in terms of length and diameter) were collected for each treatment at the ageing stage. The plants assessed had the same number of shoots (12 shoots). The number of primary and secondary leaves per shoot was counted. The leaf area of each leaf was estimated using a smartphone App (Easy Leaf Area®)[45]. Pruning weight (PW, g/plant) was measured individually during the winter on the 63 selected plants, and the average value is presented.

Yield: The harvest date was fixed according to evolution of pH (3.3 - 3.4). In addition, when these pH values were not reached for some years, priority was given to avoid dehydration of the berries (weight loss) for each treatment.Yield (Y, kg/plant) at harvest was determined on 63 individual plants per treatment.

Grape composition: At harvest, two samples of 100 berries were collected from the middle of the bunch[46] for each replicate. Individual berry weight (g) was determined for each sample. One sample was crushed using a Philips HR2290 (Philips, Netherlands) juicer. The following berry composition variables were determined: total soluble solids (TSS) by refractometry (Atago, Japan); pH by potentiometry (pH meter Hanna Instruments, Italy); and acidity by titration (gH2SO4/L), following the protocols established by the OIV[47]. Yeast readily available nitrogen content (YAN, mg/l) was determined by formaldehyde quantification[48]. The second sample was used to determine the total anthocyanin content (A, mg/l) and the total phenol index (TPI) according to the methodology proposed by Glories and Agustin[49] as modified by González-Neves and others[50]. Measurements were carried out in duplicate by spectrophotometry with a spectrophotometer (Shimadzu UV-1240 Mini, Japan). Glass cuvettes were used for the analysis of anthocyanins (absorbance at 520 nm) and quartz cuvettes for phenols (absorbance at 280 nm) with an optical path length of 1 cm.

Assessment of water use: This was carried out considering the productive and economic aspects. At the production level, water productivity (WP) was calculated. WP is the ratio between the yield (kg/ha) and the amount of water received during the same period (effective rainfall + irrigation applied)[51]. The economic valuation of the grapes was made based on the reference price of grapes in the 2020 and 2021 vintages by INAVI (*Instituto Nacional de Vitivinicultura*). According to Uruguayan regulations, wines with a probable alcohol content of more than 12% can be marketed as wines of preferential quality (*V.C.P.*). Three quality categories (A, B and C) were established according to the primary and secondary components of the grapes. Category A includes the treatment that achieved a probable alcohol of more than 12% (an exclusion requirement for entry), and obtained a higher phenolic concentration. Category B includes treatments that did not reach the probable alcohol values indicated for the V.C.P., although they obtained grapes with intermediate phenolic concentration levels. Category C includes the treatments that did not reach the alcohol content for the V.C.P. category and obtained less than 2000 mg/lof anthocyanins. Category C obtained the minimum price suggested by INAVI for each year. Category B was estimated to be 15% higher than the minimum price, while category A was estimated to be 30% higher than the minimum price. The grape prices are presented in Table 2.

Statistical analyses were performed with the statistical package InfoStat version 2011. Analyses of variance were performed, followed by Fisher's test for the comparison of means, to determine the effect of irrigation on plant response.

**Table 2.** Quality categories and grape price

| Quality category | Price per kilo (USD/kg grape) | |
|---|---|---|
| | 2020 | 2021 |
| A | 0.52 | 0.54 |
| B | 0.46 | 0.48 |
| C | 0.40 | 0.42 |

## 3. Results

### 3.1 Water available in the soil in the historical period

The water balance (WB) shows a strong annual and inter-annual variability from 2000 to 2023 (Fig. 1). In general terms, the "winter" months (from May to August in the southern hemisphere) show a positive WB, with full water reserve in the soil to initiate bud-break (except for 2008, 2018, and 2020). The WB becomes less favorable during the "summer" months (November to March).

For the HV area (Figure 1A), 51% of the months had a good water level, i.e. in categories 1 and 2 (32 and 19%, respectively), while 28% of the months of the historical series analyzed were in categories 4 and 5 (20 and 8%, respectively) with low water reserve. The remaining 21% had an intermediate water level (category 3). In contrast, for the LV area (Figure 1B), the distribution of the months in the categories determined that 50% of the months presented an excellent water reserve (category 1: 44%; category 2: 6%); intermediate water reserve (category 3: 10%) and 40% with low water reserve (category 4: 16%, and category 5: 24%). These observed changes in the distribution of water reserve categories among the soils in each vigor zone indicate that the LV zone soil saturates and dries out faster than the HV soil.

When considering only the growing period of the crop (September to April, SH), the distribution of WB for each category changes in each vigor zone. Thirty-six percent of the months show good water availability (category 1+2), 26% with an intermediate reserve (category 3), and 38% with low levels (category 4 and 5) in the HV zone. The months without deficits were those corresponding to bud-break and the establishment of the vegetative surface (September, October, November), and from summer onwards the deficits were moderate to severe in some years (2008, 2011, 2016, 2018, 2020, and 2023). For the LV zone, well-hydrated months correspond to 32% of the months (category 1+2), especially during September and October. Months with moderate deficits accounted for 11% (November and December), and months with severe deficits represented 57% (January, February and March). The LV zone has higher deficit moments with a lower proportion of months within categories 2, 3 and 4, compared to the HV area. In addition, there are years where the deficit was moderate to severe during bud-break and flowering (2003, 2005, 2008, 2018, 2020, and 2021) for plants in the LV zone.

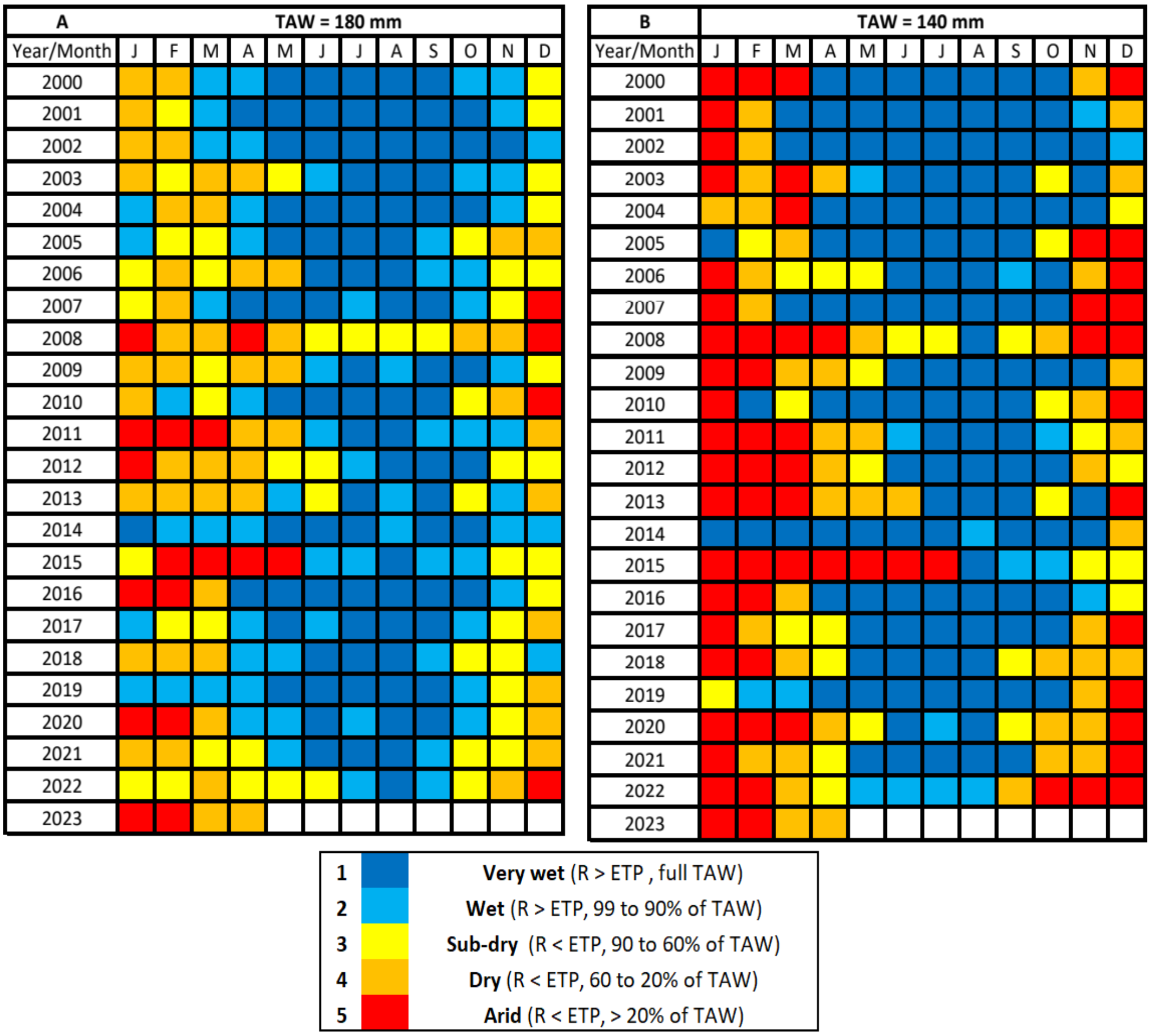



**Figure 1.** Inter- and intra-annual variability of the water balance from 2000 to 2023

A- Soil corresponding to the high vigor zone, with a TAW of 180 mm. B- Soil corresponding to the low vigor zone, with a TAW of 140 mm. R: rain; ETP: Evapotranspiration potential; TAW: Total Available Water

## 3.2 Climate characterization of the study years (2020 and 2021)

The crop cycles show differences in water supply and demand (Fig. 2). In 2020, the water supply was 484 mm, while in 2021, it was 539 mm. The years also differed in the timing of rainfall. In 2020, 60% of the rainfall occurred between bud-break and flowering (September, October and November), and 25% between flowering and veraison. The remaining 15% occurred between veraison and harvest. On the other hand, in 2021, the highest water supply occurred between veraison and harvest with 48%, followed by the period between bud-break and bloom (31%), and the remaining 22% between flowering and veraison. Atmospheric demand (ETo) was 903 mm in 2020 and 853 mm in 2021. The water balance (accumulated rainfall - accumulated water) was negative in both seasons (-419 mm in 2020 and -300 mm in 2021). Air temperature was similar in both years, with 2020 being slightly warmer in terms of mean, maximum and minimum temperature (1 °C higher) compared to 2021. In 2020 the warmest month was February (29.5 °C); in 2021, it was January (29.6 °C).

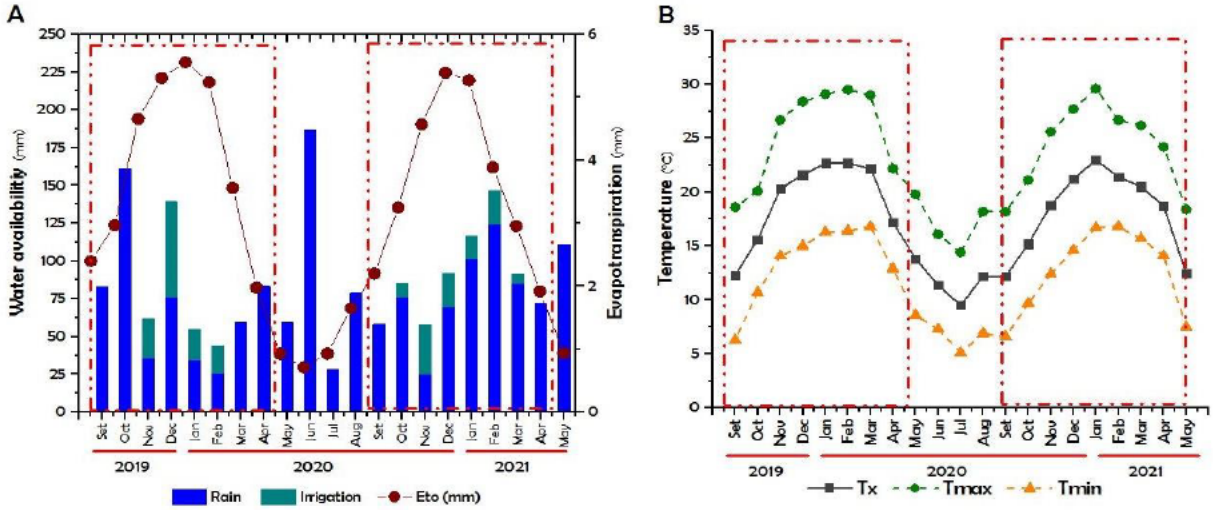



**Figure 2.** Macroclimatic characterization for the study site during 2020 and 2021 seasons

A. Monthly evolution of water availability and reference evapotranspiration. Water availability is the sum of precipitation and irrigation provided in the irrigation treatment. B. Air temperature evolution. Tx: mean temperature; Tmax: maximum temperature; Tmin: minimum temperature. Red lines indicate the years of evaluation.

### 3.3 Supplementary water supply for the 2020 and 2021 seasons

Irrigation supplemented the water supply during October, November, December, January and February (Figure 2). In 2020, 160 mm were applied in 28 irrigations (Table 3). In 2021, 21 irrigations were made and 120 mm were applied. The water balance (Table 3) ranged from very wet at bud-break to wet at bloom for both treatment and crop cycles (with the exception of the control in 2021). In 2020, the period with the highest soil water deficit was pre-harvest, where the control treatment I had the highest deficit (category 4). At the same time, the irrigation treatment (I) improved water availability at veraison and pre-harvest (categories 3 and 4). In 2021, the highest water deficit occurred at veraison for treatment C, while treatment I maintained the soil profile with more than 60% of the TAW.

**Table 3.** Soil water supply and soil water balance for each treatment

| Year | Treatment | Rain (mm) | Irrigation (mm) | Water balance | | | |
|---|---|---|---|---|---|---|---|
| | | | | BB | Bl | V | H |
| 2020 | Control | 484 | 0 | | | | |
| | Irrigation | 484 | 160 | | | | |
| 2021 | Control | 539 | 0 | | | | |
| | Irrigation | 539 | 120 | | | | |

Acronyms represent 8 phenological stages: BB (bud-break); Bl (bloom); V (veraison) and H (harvest). Blue: category 1 (Very wet); light blue: category 2 (Wet); yellow: category 3 (Sub-dry); orange: category 4 (Dry); red: category 5 (Arid).

### 3.4 Plant response to water availability

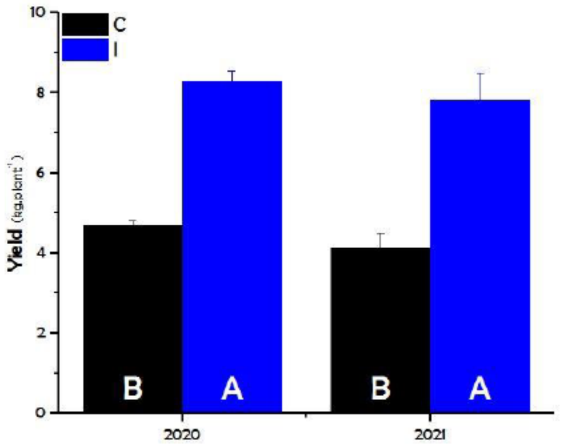
The plant water availability showed differences between years and between treatments (Table 4). In 2020, water potential ($\psi_b$) values were lower than those obtained in 2021. Water stress index (WSI) values were higher in treatment C thanin treatment I in response to lower water potentials (-0.30 to -0.85 MPa). Higher $\psi_b$values (above -0.35 MPa) in both seasons resulted in lower WSI in treatment I.

**Table 4.** Vegetative growth variables by treatment and production cycle

| Year | Treatments | WSI (MPa.day-1) | Kc max | TLA (m2.plant-1) | PW (g.plant-1) |
|---|---|---|---|---|---|
| 2020 | Control | 34.0 ± 2.2 a | 0.42 ± 0.07 b | 1.7 ± 0.75 b | 341 ± 65 b |
| | Irrigation | **9.3 ± 1.2 b** | **0.70 ± 0.03 a** | **5.3 ± 1.07 a** | **505 ± 33 a** |
| 2021 | Control | 25.7 ± 1.8 a | 0.56 ± 0.02 b | 3.5 ± 0.25 b | 172 ± 15 b |
| | Irrigation | **7.7 ± 1.0 b** | **0.76 ± 0.02 a** | **7.9 ± 0.10 a** | **392 ± 45 a** |

Average values and standard deviation. WSI: water stress index. Kcmax: Maximum crop coefficient. TLA: Total Leaf Area. PW: Pruning weight. Different letters indicate significant differences according to Fisher (p-value<0.05) between treatments for each year evaluated.

**Figure 3.** Yield per plant by treatment and production cycle




Total leaf area was higher in 2021 in both treatments compared to 2020. The irrigated treatment presented a higher leaf area (35 EyL) than C. The maximum Kc reached by the plants was 27% higher in the irrigated treatment for both crop cycles. The higher leaf area was also reflected in a higher pruning weight in the irrigated treatment. A year effect was also observed, with higher PW in 2020.

For each treatment, the yield was similar in the two years evaluated (Fig. 3). The treatment I doubled the yield in both years compared to C in rainfed conditions. This increase in yield is explained by higher berry weight (Table 5) and higher bunch weight (data not shown).

For the primary composition parameters, I treatment showed higher total soluble solids content than the control in 2020 and 2021 (Table 5). For the variable yeast-assimilable nitrogen (YAN), a significant increase of around 60% was found with higher water availability (average 2020 and 2021). No differences in acidity were observed between treatments for both years of evaluation. In terms of secondary metabolism, anthocyanin and phenol accumulation was higher in 2020 compared to 2021. The effect of irrigation (I) on these metabolites was expressed by an increase in anthocyanins (A) concentration in both years. Phenols (TPI) was higher only in 2020 for treatment I compared to C.

**Table 5.** Berry weight and grape composition by treatment

| Year / Treatments | | Bw (g) | TSS (g/l) | TA (g.l-1 sulfuric) | YAN (mg L-1) | A (mg/l) | TPI |
|---|---|---|---|---|---|---|---|
| 2020 | C | 0.95 ± 0.15 b | 203 ± 7 b | 4.5 ± 0.14 | 67 ± b | 1692 ± 158 b | 61 ± 3.7 b |
| | I | **1.51 ± 0.10 a** | **223 ± 9 a** | 4.4 ± 0.16 | **125 ± a** | **2425 ± 135 a** | **77 ± 4.0 a** |
| 2021 | C | 1.14 ± 0.11 b | 197 ± 5 b | 4.1 ± 0.20 | 110 ± b | 1694 ± 94 b | 52 ± 6.0 |
| | I | **1.48 ± 0.06 a** | **220 ± 3 a** | 4.3 ± 0.25 | **162 ± a** | **2110 ± 90 a** | 57 ± 3.5 |

C: Control treatment. I: Irrigation treatment. Different letters indicate significant differences according to Fisher (p-value < 0.05) between treatments for each year evaluated.

### 3.5 Water productivity and economic evaluation

The differences in yield and grape composition allow us to evaluate the impact of supplementary water supply (Table 6). Water productivity (WP) was higher in the irrigated treatment compared to the control in both years (+42%). Although water inputs were higher in treatment I, the increase in yield was more influential in increasing WP.

Treatment C, in neither of the two years evaluated, reached the minimum soluble solids level required to obtain V.C.P. wines (12% v/v of probable alcohol), and the grapes could be marketed as category B. Treatment I, on the other hand, presented levels of probable alcohol that exceeded the minimum required so that it could be marketed as category A. The differences in yield and price according to wine category explain the differences in gross income between treatments.

**Table 6.** Productive and economic assessment of water use

| Year | Treatments | WP (kg m$^{-3}$) | Qualitycategory | Gross Margin (USD/ha) | Incomedifference (%) |
|---|---|---|---|---|---|
| **2020** | Control | 3.23 | B | 7205 | - |
| | Irrigation | 4.24 | A | 14211 | 97 |
| **2021** | Control | 2.53 | B | 6559 | - |
| | Irrigation | 3.94 | A | 14038 | 114 |

## 4. Discussion

### 4.1 Plant response to water availability

The water balance in a vineyard is not only conditioned by the water supply (rainfall + irrigation), but also depends on the capacity of the soil to reserve water and how quickly it can evaporate. The trial years were similar in terms of water supply and demand, with 2020 being the year with the highest water deficit compared to 2021. Under these climatic conditions (Figure 2), additional water inputs through a controlled deficit irrigation (RDI) strategy improved plant response (Table 4, 5, and Fig. 3). Irrigated plants were able to maintain a better water status (moderate water stress) than rainfed plants (severe water stress) (Table 3, 4)[28]. This resulted in higher vegetative growth and crop Kc (Table 4). Vegetative growth, particularly secondary growth[28], is susceptible to water and nitrogen availability[52-53]. Other studies also report that the water applied stimulates vegetative growth and pruning weight[26][54]. This impact was reflected in higher yield and berry weight, in agreement with other reports[55-56]. Yield increases with RDI have even been reported under sub-humid conditions and high-water reserve capacity in soils[25]. Similarly, a null effect of irrigation on yield parameters has been reported[26] in contradiction to our results. Higher carbon availability under moderate water deficit conditions could explain the yield increase[10-12].

Maintaining the plants under moderate water deficit conditions (I) stimulated the accumulation of sugars and anthocyanins (Table 5), as reported in other studies[57-58]. The increase in berry metabolites has been related to a smaller berry size (lower skin:pulp ratio), and is therefore considered a desirable factor especially for red wines[59]. Also, reducing vegetative vigor due to water deficit improves the microclimate at the cluster level (light and temperature), and thus stimulates the accumulation of metabolites[60]. Our results show that additional water supply has played a more critical role in accumulating primary and secondary compounds[12], even when vegetative growth and berry weight are greater. Higher production of assimilates (due to better water comfort) and a greater distribution of these assimilates to the ripening berries[57] would explain the higher accumulation in the irrigated vines. Moreover, although the plants were better hydrated, they maintained a water deficit that stimulated the expression of genes responsible for the biosynthesis of these metabolites, especially anthocyanins[61], independently of changes in the morphological or anatomical characteristics of the berries[62]. The non-irrigated condition (C) reached severe stress levels (Table 1) during ripening, which inhibited photosynthetic processes[54] with a negative impact on sugar and anthocyanin accumulation in the berries (Table 1).

### 4.2 Irrigation requirements in sub-humid climates

Variability in plant vigor within vineyards or in the same vineyard has been widely reported[63-64], even in 1.1 ha vineyard[30]. This vineyard has two contrasting vigor zones[30], and these differences were stable over time, as reported by other studies[63]. Variations in vigor are associated with heterogeneity of soil parameters[65-66]. The most important factors defining a soil's water holding capacity are such as soil texture, soil depth, and organic matter content. Variations in soil depth and texture determine the rooting depth of the vine, and therefore contribute to the determination of the plant's water balance and the expression of vigor[41][67-68]. These differences in soil water storage capacity mean that vigor zones have different sensitivities to water deficit. In the simulation of the vineyard water balance, the soil with the lowest water reserve (LV) was more susceptible to months of excess of water and water deficit than the soil with the highest water reserve (HV), as reported for Mediterranean vineyards[40]. Plants in the LV zone presented 57% of the months of the growing cycle with an arid condition in WB, while in the HV zone, these months represented 38%. This shows that water needs were greater in the LV, but both soils needed supplementary water.

Another aspect to consider is that the water balance was modeled based on methodologies proposed for a Mediterranean vineyard without cover crops in the soil[40]. This situation does not reflect the reality of Uruguayan viticulture, where cover crops (planted or spontaneous) are present in the vineyards. The presence of vegetation in the inter-row can lead to competition for water and nitrogen[69-70], especially at times of low water availability. The management of vegetation cover is a factor to be considered in the water balance, especially under pedoclimatic conditions of high water availability, such as those in Uruguay. Tomaz and others[70] found a reduction in vine photosynthesis (during a dry spring) associated with increased competition for water from plant cover. Such a situation would be more plausible for vines in the low vigor zone of our study. In years or periods of higher water supply, the cover cropsplay a role in limiting the vegetative vigor of the vine due to this competition effect. Excess water stimulates vegetative growth, with less exposure of the clusters, lower quality and phytosanitary problems. This situation would be more aggravated in a plot with a high water reserve capacity (HV zone in our trial).

### 4.3 Opportunities and challenges

Agriculture is one of the world's largest water-consuming sectors. It is estimated that 70% of freshwater irrigates 25% of cultivated land[71]. Within the climate change outlook, the FAO (Food and Agriculture Organisation of the United Nations) forecasts a 50% increase in irrigated agriculture by 2050[71]. Therefore, the pressure on water use will be greater and efforts should be focused on improving water use efficiency.

Differences in vigor within a plot are associated with the heterogeneity of soil parameters and tend to be stable over time. If this variability can be understood and characterized, the vineyard can be divided into homogeneous management zones to allow differential management and thus optimize the use of resources. In this approach, productivity is maximized through a reasoned use of resources according to their needs[72]. Differential irrigation according to vigor zones has been reported to increase yield, water use efficiency and grape composition (in low vigor zones), and reduce water input in the high vigor zone[72-73].

The results of our trial indicate that controlled deficit irrigation is a suitable option for maintaining good yields with good quality in all vineyards, but especially in vineyards planted on soils with low water reserve capacity in critical periods for vegetative development and ripening. This technique optimizes production and improves economic indicators by ensuring a product that can be marketed with a differential value. Although our analysis does not include production costs (associated with the installation of an irrigation system, maintenance, energy, and access to water), the changes in production parameters seem to justify the use of the technique. Because small water supplements applied correctly improved yield and grape quality, these results were stable over time, as reported in other studies[74-75]. Associated to this site-specific management strategy, defining how much and when to irrigate is one of the key aspects for success. In traditional irrigation systems, changes in meteorological variables or spatio-temporal variations in soil characteristics are not considered[76]. The challenge is to optimize water use through smart irrigation systems that monitor weather, soil and plant conditions in real-time (via sensors)[77]. Smart irrigation is irrigation that delivers the required water at the right time and at the right place in the field[78]. This strategy avoids the application of excessive water sheets, which can lead to fertilizer leaching, waterlogging or surface run-off, saving time and money[79]. In this sense, precision agriculture technologies can contribute to an improvement in smart irrigation planning.

In the context of climate change, the increase in the timing of periods with water deficits and heat wave phenomena can cause most damage to winegrowers. The water status of the crop during a heat wave can cushion the damage caused by these phenomena[80]. In Australia, it is generally recommended to carry out supplementary irrigations before a heat wave warning. This favors canopy cooling due to increased evapotranspiration[81]. Moreover, as climate reports can predict these phenomena well in advance, the winegrower can prepare to mitigate damage before they occur[82]. This study demonstrated its productive and economic validity in years with low water supply. In years with excess water or soils with a high soil water reserve capacity, the water demands of the cover crop should be considered in the water balance to avoid an excessive limitation of vine vigor once the period of the excess water has passed.

Access to water is another factor to consider when defining irrigation planning. There are limitations in the use of irrigation in Uruguayan viticulture. These limitations refer to logistical aspects and access to water[81]. Generally, in Uruguayan vineyards with irrigation the systematization and pumping capacity is not optimal to cover the plants' water needs in very dry seasons or in all vineyards. Access to water in certain regions is one of the most critical points limiting the expansion of the technique. The use of other water sources for irrigation, such as treated wastewater (TWW), has been tested in vineyards and other crops. In the case of vineyards, advantages in yield and grape quality have been reported using TWW[83]. The use of TWW should be done with caution because the content of nutrients and salts is highly dependent on the origin of the wastewater (field or city) and the treatment performed[83].

## 5. Conclusions and perspectives

Given the climatic characteristics of the years studied, controlled deficit irrigation proved to be a valid technique for improving production and economic indicators. The supplementary water supply at specific times led the plants to show better water "comfort", resulting in a better leaf:fruit balance, allowing higher yields with a greater accumulation of sugars and anthocyanins. The simulation of the water balance (even with its limitations) made it possible to evaluate the water needs of the vineyard and to assess the role of the soil in buffering the water deficit. This could be used to define the periods in which to irrigate.

Characterizing the variability present in the vineyard, especially in relation to root depth and the soil's water reserve capacity, is one of the key factors in determining when to irrigate and what the crop's real water needs are. The new technologies, such as the use of smartphones and real-time sensors, are tools that will help the vine grower to make decisions regarding irrigation. Deficit and controlled irrigation management seems to be validated in sub-humid areas, but it is necessary to continue generating knowledge about all of them in years of higher water supply. Also, the role of cover crops in the vineyard water balance should be considered in future analyses.

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### Transparency of data

Data not available: The data set that supports the results of this study is not publicly available. For further information please contact the first author.

### Author contribution statement

MF: Conceived and designed the analysis. GP: Collected the data, performed the analysis, and wrote the paper.

## References

1. Wan Y, Schwaninger H, Li D, Simon CJ, Wang Y, He P. The ecogeographic distribution of wild grapegermplasm in China. Vitis. 2008;47:77-80.

2. Williams LE, Matthews MA. Grapevine. In: Stewart BA, Nielson NR, editors. Irrigation of agricultural crops. Madison: ASA; 2009. pp. 1019-55.

3. Williams LE. Determination of evapotranspiration and crop coefficients for a Chardonnay vineyard located in a cool climate. Am J Enol Vitic. 2014;65:159-69. Doi: 10.5344/ajev.2014.12104.

4. Williams LE, Baeza P. Relationships among ambient temperature and vapor pressure deficit and leaf and stem water potentials of fully irrigated, field-grown grapevines. Am J Enol Vitic. 2007;58:173-81. Doi: 10.5344/ajev.2007.58.2.173.

5. Cid Y, Miras-Avalos J. Necesidades hídricas del viñedo. Wetwine. 2019;3:4-9.

6. Carbonneau A. Aspects qualitatifs. In: Tiercelin JR, Lavoiser T, editors. Proceedings 17th World Congress of Vine and Wine; 1998; Bratislava. Bratislava: Tec & Doc Lavoisier; 1998. pp. 258-76.

7. Deloire A, Carbonneau A, Wang Z, Ojeda H. Vine and water: a short review. OENO One. 2004;38(1):1-13. Doi: 10.20870/oeno-one.2004.38.1.932.

8. Ojeda H. Riego cualitativo de precisión en la vid. Revista Enología. 2007;1:14-7.

9. Williams LE, Dokoozlian NK, Wample R. Grape. In: Schaffer B, Andersen PC, editors. Handbook of Environmental Physiology of Fruit Crops. Vol. 1, Temperate Crops. Boca Raton: CRC Press; 1994. pp. 85-133.

10. Guilpart N, Metay A, Gary C. Grapevine bud fertility and number of berries per bunch are determined by water and nitrogen stress around flowering in the previous year. Eur J Agron. 2014;54:9-20. Doi: 10.1071/FP14062.

11. Lu Z, Neumann PM. Water-stressed maize, barley and rice seedlings show species diversity in mechanisms of leaf growth inhibition. J Exp Bot. 1998;49(329):1945-52.

12. Ojeda H, Andary C, Kraeva E, Carbonneau A, Deloire A. Influence of pre- and postveraison water deficit on synthesis and concentration of skin phenolic compounds during berry growth of Vitis vinifera cv. Shiraz. Am J Enol Vitic. 2002;53:261-7.

13. Champagnol F. Elements of the physiology of the vine and of general viticulture. Montpellier: Dehan; 1984. 351p.

14. Tiscornia G, Cal A, Gimenez A. Análisis y caracterización de la variabilidad climática en algunas regiones de Uruguay. RIA. 2016;42(1):66-71.

15. Docampo R, Silva A. Suelos y su manejo. In: Grompone MA, Villamil J, editors. Aceites de oliva: de la planta al consumidor. Vol. 1. Montevideo: Hemisferio Sur; 2013. pp. 91-122.

16. IPCC. Summary for Policymakers. In: Climate Change 2007: the physical science basis [Internet]. Cambridge: Cambridge University Press; 2007 [cited 2023 Sep 5]. 18p. Available from: https://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

17. IPCC. Summary for Policymakers. In: Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Internet]. Cambridge: Cambridge University Press; 2008 [cited 2023 Sep 5]. 24p. Available from: https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SPM_version_report_LR.pdf

18. Nairn JR, Fawcett RG. Defining heatwaves: heatwave defined as a heat-impact event servicing all community and business sectors in Australia. Kent Town: Centre for Australian Weather and Climate Research; 2013. 84p.

19. Plan Nacional de Adaptación a la variabilidad y el cambio climático para el sector agrícula [Internet]. Montevideo: MGAP; 2019 [cited 2023 Sep 5]. 125p. Available from: https://bit.ly/45npBYk

20. Pagay V, Collins C. Effects of timing and intensity of elevated temperatures on reproductive development of field-grown Shiraz grapevines. OENO One. 2017;51(4). Doi: 10.20870/oeno-one.2017.51.4.1066.

21. Sadras VO, Moran MA. Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc. Aust J Grape Wine Res. 2012;18(2):115-22.

22. Gambetta JM, Holzapfel BP, Stoll M, Friedel M. Sunburn in grapes: a review. Front Plant Sci. 2021;11:604691. Doi: 10.3389/fpls.2020.604691.

23. Dry PR, Loveys BR, McCarthy MG, Stoll M. Strategic irrigation management in Australian vineyards. OENO One. 2001;35(3):129-39. Doi: 10.20870/oeno-one.2001.35.3.1699.

24. Chaves MM, Zarrouk O, Francisco R, Costa JM, Santos T, Regalado AP, Rodrigues ML, Lopes CM. Grapevine under deficit irrigation: hints from physiological and molecular data. Ann Bot. 2010;105(5):661-76. Doi: 10.1093/aob/mcq030.

25. Battilani A, Mannini P, Anconelli S. Grapevine irrigation scheduling in the Po Valley sub-humid area. Irrigazione e Drenaggio. 2000;47(4):15-9.

26. Trigo-Córdoba E, Bouzas-Cid Y, Orriols-Fernández I, Mirás-Avalos JM. Effects of deficit irrigation on the performance of grapevine (Vitis vinifera L.) cv.'Godello'and 'Treixadura'in Ribeiro, NW Spain. Agric Water Manag. 2015;161:20-30. Doi: 10.1016/j.agwat.2015.07.011.

27. Mirás-Avalos JM, Trigo-Córdoba E, Bouzas-Cid Y, Orriols-Fernández I. Irrigation effects on the performance of grapevine (Vitis vinifera L.) cv. 'Albariño' under the humid climate of Galicia. OENO One. 2016;50(4). Doi: 10.20870/oeno-one.2016.50.4.63.

28. Pereyra G, Pellegrino A, Gaudin R, Ferrer M. Evaluation of site-specific management to optimise Vitis vinifera L.(cv. Tannat) production in a vineyard with high heterogeneity. OENO One. 2022;56(3):397-412. Doi: 10.20870/oeno-one.2022.56.3.5485.

29. INAVI. Estadísticas de Viñedos 2022: datos nacionales [Internet]. Canelones: INAVI; 2023 [cited 2023 Sep 5]. 66p. Available from: https://www.inavi.com.uy/uploads/vinedo/e114169ff8dd5bd2a83547b5a8c60636eb4aebcc.pdf

30. Ferrer M, Echeverría G, Pereyra G, Gonzalez-Neves G, Pan D, Mirás-Avalos JM. Mapping vineyard vigor using airborne remote sensing: relations with yield, berry composition and sanitary status under humid climate conditions. Precis Agric. 2020;21(1):178-97. Doi: 10.1007/s11119-019-09663-9.

31. Silva A, Docampo R, Camejo C, Barboza C. Inventario de suelos bajo viña: principales características edafológicas de los viñedos uruguayos. Montevideo: INIA; 2018. 164p.

32. FAO. Guidelines for soil description [Internet]. 4th ed. Rome: FAO; 2006 [cited 2023 Sep 5]. 97p. Available from: https://www.fao.org/3/a0541e/a0541e.pdf

33. Soil Survey Staff. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. 2nd ed. Washington: USDA; 1999. 871p.

34. Williams LE, Ayars JE. Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy. Agric For Meteorol. 2005;132:201-11. Doi: 10.1016/J.AGRFORMET.2005.07.010.

35. Alliaume F, González Barrios P, Echeverría G, Ferrer M. Characterization of spatial variability of soils within a vineyard for management zones determination. In: Carbonneau A, Torregrosa L, editors. XXth GIESCO International Meeting; 2017 Nov; Mendoza, Argentina [Internet]. Mendoza: GIESCO; 2017 [cited 2023 Sep 5]. pp. 787-91. Subscription required to view. Available from: https://bit.ly/452ihkB

36. Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration: guidelines for computing crop water requirements. Rome: FAO; 1998. 300p.

37. Fernández CJ. Estimaciones de la densidad aparente y retención de agua disponible en el suelo. In: 2a Reunión Técnica Facultad de Agronomía; 27 - 29 noviembre 1979, Montevideo. Montevideo: Universidad de la República; 1979. pp. S2.

38. Silva A, Ponce de León J, García F, Durán A. Aspectos metodológicos en la determinación de la capacidad de retener agua de los suelos del Uruguay. Boletín de Investigación. 1988;(10):20p.

39. Pereyra G, Ferrer M, Pellegrino A, Gaudin R. Montmorillonite content is an influential soil parameter of grapevine development and yield in South Uruguay. Agrocienc Urug. 2022;26(2):e1124. Doi: 10.31285/AGRO.26.1124.

40. Gaudin R, Gary C. Model-based evaluation of irrigation needs in Mediterranean vineyards. Irrig Sci. 2012;30:449-59. Doi: 10.1007/s00271-012-0349-x.

41. Lamy C. Impact du changement climatique sur la fréquence et l'intensité des sécheresses en Bretagne [doctoral's thesis]. Rennes (FR): Université Rennes 2; 2013. 274p.

42. Myers BJ. Water stress integral: a link between short-term stress and long-term growth. Tree physiol. 1988;4(4):315-23. Doi: 10.1093/treephys/4.4.315.

43. Bernard N, Zebic O, Deloire A. Estimation de l´état hydrique de vigne par la mesure de la température foliare: un outil au service des professionnels. Le Progrès Agricole et Viticole. 2004;23:539-42.

44. De Bei R, Fuentes S, Gilliham M, Tyerman S, Edwards E, Bianchini N, Collins C. VitiCanopy: a free computer App to estimate canopy vigor and porosity for grapevine. Sensors. 2016;16(4):585. Doi: 10.3390/s16040585.

45. Easlon HM, Bloom AJ. Easy Leaf Area: automated digital image analysis for rapid and accurate measurement of leaf area. Appl Plant Sci. 2014;2(7):apps.1400033. Doi: 10.3732/apps.1400033.

46. Deloire A, Pellegrino A, Ristic R. Spatial distribution of berry fresh mass, seed number and sugar concentration on grapevine clusters of Shiraz. Wine & Viticulture Journal. 2019;34:42-7.

47. OIV. Compendium of International Methods of Analysis of Wines and Musts Analysis [Internet]. Vol. 1. Paris: OIV; 2021 [cited 2023 Sep 5]. 673p. Available from: https://www.oiv.int/public/medias/7907/oiv-vol1-compendium-of-international-methods-of-analysis.pdf

48. Aerny J. Composés azotés des moûts et des vins. RSVAH. 1996;28(3):161-5.

49. Glories Y, Agustin M. Maturité phénolique du raisin, conséquences technologiques: application aux millésimes 1991 et 1992. Compte Rendu Colloque Journée Techniques. 1993;56-61.

50. González-Neves G, Charamelo D, Balado J, Barreiro L, Bochicchio R, Gatto G, Gil G, Tessore A, Carbonneau A, Moutounet M. Phenolic potential of Tannat, Cabernet-Sauvignon and Merlot grapes and their correspondence with wine composition. Anal Chim Acta. 2004;513:191-6. Doi: 10.1016/j.aca.2003.11.042.

51. Pedrero F, Maestre-Valero JF, Mounzer O, Alarcón JJ, Nicolás E. Physiological and agronomic mandarin trees performance under saline reclaimed water combined with regulated deficit irrigation. Agric Water Manag. 2014;146:228-37.

52. Metay A, Magnier J, Guilpart N, Christophe A. Nitrogen supply controls vegetative growth, biomass and nitrogen allocation for grapevine (cv. Shiraz) grown in pots. Funct Plant Biol. 2014;42(1):105-14. Doi: 10.1071/FP14062.

53. Vrignon-Brenas S, Metay A, Leporatti R, Gharibi S, Fraga A, Dauzat M, Rolland G, Pellegrino A. Gradual responses of grapevine yield components and carbon status to nitrogen supply. Oeno One. 2019;53:289-306. Doi: 10.20870/oeno-one.2019.53.2.2431.

54. Intrigliolo DS, Castel JR. Vine and soil-based measures of water status in a Tempranillo vineyard. Vitis. 2006;45(4):157-63.

55. Reynolds AG, Senchuk IV, van der Reest C, de Savigny C. Use of GPS and GIS for elucidation of the basis for terroir: spatial variation in an Ontario Riesling vineyard. Am J Enol Vitic. 2007;58:145-62. Doi: 10.5344/ajev.2007.58.2.145.

56. Basile B, Girona J, Behboudian MH, Mata M, Rosello J, Ferré M, Marsal J. Responses of "Chardonnay" to deficit irrigation applied at different phenological stages: vine growth, must composition, and wine quality. Irrig Sci. 2012;30:397-406.

57. Romero P, Gil-Muñoz R, del Amor FM, Valdes E, Fernández JI, Martinez-Cutillas A. Regulated deficit irrigation based upon optimum water status improves phenolic composition in Monastrell grapes and wines. Agric Water Manag. 2013;121:85-101. Doi: 10.1016/j.agwat.2013.01.007.

58. Alatzas A, Theocharis S, Miliordos DE, Kotseridis Y, Koundouras S, Hatzopoulos P. Leaf removal and deficit irrigation have diverse outcomes on composition and gene expression during berry development of Vitis vinifera L. cultivar Xinomavro. OENO One. 2023;57(1):289-305. Doi: 10.20870/oeno-one.2023.57.1.7191.

59. Koundouras S, Hatzidimitriou E, Karamolegkou M, Dimopoulou E, Kallithraka S, Tsialtas JT, Zioziou E, Nikolaou N, Kotseridis Y. Irrigation and rootstock effects on the phenolic concentration and aroma potential of Vitis vinifera L. cv. cabernet sauvignon grapes. J Agric Food Chem. 2009;57(17):7805-13. Doi: 10.1021/jf901063a.

60. Mori K, Goto-Yamamoto N, Kitayama M, Hashizume K. Loss of anthocyanins in red-wine grape under high temperature. J Exp Bot. 2007;58(8):1935-45. Doi: 10.1093/jxb/erm055.

61. Savoi S, Wong DC, Arapitsas P, Miculan M, Bucchetti B, Peterlunger E, Fait A, Mattivi F, Castellarin SD. Transcriptome and metabolite profiling reveals that prolonged drought modulates the phenylpropanoid and terpenoid pathway in white grapes (Vitis vinifera L.). BMC Plant Biol. 2016;16:67. Doi: 10.1186/s12870-016-0760-1.

62. Roby G, Matthews MA. Relative proportions of seed, skin and flesh, in ripe berries from Cabernet Sauvignon grapevines grown in a vineyard either well irrigated or under water deficit. Aust J Grape Wine Res. 2004;10:74-82. Doi: 10.1111/j.1755-0238.2004.tb00009.x.

63. Bramley RGV, Hamilton RP. Understanding variability in winegrape production systems: 1. Within vineyard variation in yield over several vintages. Aust J Grape Wine Res. 2004;10(1):32-45. Doi: 10.1111/j.1755-0238.2004.tb00006.x.

64. Taylor JA, Acevedo-Opazo C, Ojeda H, Tisseyre B. Identification and significance of sources of spatial variation in grapevine water status. Aust J Grape Wine Res. 2010;16:218-26. Doi: 10.1111/j.1755-0238.2009.00066.x.

65. Tardaguila J, Baluja J, Arpon L, Balda J, Oliveira M. Variations of soil properties affect the vegetative growth and yield components of "Tempranillo" grapevines. Precis Agric. 2011;12:762-73. Doi: 10.1007/s11119-011-9219-4.

66. Priori S, Pellegrini S, Perria R, Puccioni S, Storchi P, Valboa G, Costantini EAC. Scale effect of terroir under three contrasting vintages in the Chianti Classico area (Tuscany, Italy). Geoderma. 2019;334:99-112. Doi: 10.1016/j.geoderma.2018.07.048.

67. van Leeuwen C, Friant P, Chone X, Tregoat O, Koundouras S, Dubourdieu D. Influence of climate, soil, and cultivar on terroir. Am J Enol Vitic. 2004;55:207-17. Doi: 10.5344/ajev.2004.55.3.207.

68. Pagay V, Furlan TS, Kidman CM, Nagahatenna D. Long-term drought adaptation of unirrigated grapevines (Vitis vinifera L.). Theor Exp Plant Physiol. 2022;34(2):215-25. Doi: 10.1007/s40626-022-00243-3.

69. Celette F, Gaudin R, Gary C. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. Eur J Agron. 2008;29:153-62. Doi: 10.1016/j.eja.2008.04.007.

70. Tomaz A, Coleto Martinez J, Pacheco CA. Effects of cover crops and irrigation on 'Tempranillo' grapevine and berry physiology: an experiment under the Mediterranean conditions of Southern Portugal. Oeno One. 2021;55(3):191-208. Doi: 10.20870/oeno-one.2021.55.3.4629.

71. FAO. The state of food and agriculture 2020: overcoming water challenges in agriculture. Rome: FAO; 2020. 178p. Doi: 10.4060/cb1447en.

72. McClymont L, Goodwin I, Mazza M, Baker N, Lanyon DM, Zerihun A, Downey MO. Effect of site-specific irrigation management on grapevine yield and fruit quality attributes. Irrig Sci. 2012;30:461-70. Doi: 10.1007/s00271-012-0376-7.

73. Oldoni H, Costa BRS, Bognola IA, Souza CR, Bassoi LH. Homogeneous zones of vegetation index for characterizing variability and site-specific management in vineyards. Sci agric (Piracicaba, Braz.). 2020;78(4). Doi: 10.1590/1678-992X-2019-0243.

74. Matthews MA, Ishii R, Anderson MM, O'Mahony M. Dependence of wine sensory attributes on vine water status. J Sci Food Agric. 1990;51(3):321-35. Doi: 10.1002/jsfa.2740510305.

75. Esteban MA, Villanueva MJ, Lissarrague JR. Effect of irrigation on changes in the anthocyanin composition of the skin of cv Tempranillo (Vitis vinifera L) grape berries during ripening. J Sci Food Agric. 2001;81(4):409-20. Doi: 10.1002/1097-0010(200103)81:4<409::AID-JSFA830>3.0.CO;2-H.

76. Vories E, O'Shaughnessy S, Sudduth K, Evett S, Andrade M, Drummond S. Comparison of precision and conventional irrigation management of cotton and impact of soil texture. Precis Agric. 2021;22:414-31. Doi: 10.1007/s11119- 020-09741-3.

77. Bwambale E, Abagale FK, Anornu GK. Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: a review. Agric Water Manag. 2022;260:107324. Doi: 10.1016/j.agwat.2021.107324.

78. Singh U, Praharaj CS, Gurjar DS, Kumar R. Precision irrigation management: concepts and applications for higher use efficiencyin field crops. In: Scaling Water Productivity and Resource Conservation in Upland Field Crops Ensuring More Crop per Drop. Kampur: ICAR; 2019. p. 181-90.

79. Abioye EA, Abidin MSZ, Mahmud MSA, Buyamin S, AbdRahman MKI, Otuoze AO, Ramli MSA, Ijike OD. IoT-based monitoring and data-driven modelling of drip irrigation system for mustard leaf cultivation experiment. Inf Process Agric. 2021;8:270-83. Doi: 10.1016/j.inpa.2020.05.004.

80. Webb L, Whiting J, Watt A, Hill T, Wigg F, Dunn G, Barlow EWR. Managing grapevines through severe heat: a survey of growers after the 2009 summer heatwave in south-eastern Australia. J Wine Res. 2010;21(2-3):147-65. Doi: 10.1080/09571264.2010.530106.

81. Garcia-Tejera O, Bonada M, Petrie PR, Nieto H, Bellvert J, Sadras VO. Viticulture adaptation to global warming: modelling gas exchange, water status and leaf temperature to probe for practices manipulating water supply, canopy reflectance and radiation load. Agric For Meteorol. 2023;331:109351. Doi: 10.1016/j.agrformet.2023.109351.

82. Grace WJ, Sadras VO, Hayman PT. Modelling heatwaves in viticultural regions of southeastern Australia. Aust Meteorol Oceanogr J. 2009;58(4):249.

83. Etchebarne F, Aveni P, Escudier JL, Ojeda H. Reuse of treated wastewater in viticulture: Can it be an alternative source of nutrient-rich water? BIO Web Conf. 2019:12. Doi: 10.1051/bioconf/20191201009.