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Article

AGRONOMIC AND MUST QUALITY PERFORMANCE OF *VITIS VINIFERA* L. *CV.* 'LOUREIRO': A FOUR-YEAR STUDY

DESEMPENHO AGRÓNOMICO E QUALIDADE DO MOSTO DE *VITIS VINIFERA* L. *CV.* 'LOUREIRO': QUATRO ANOS DE ESTUDO

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SUMMARY

In the Vinho Verde region, one of the most widely cultivated grapevine varieties is *Vitis vinifera* L. *cv.* 'Loureiro', which is produced under a rainfed conditions. However, irrigation is increasing being implemented to mitigate the effects of climate change. In this sense, the present study evaluated three different irrigation management strategies - rainfed (R), deficit irrigation (DI) and irrigation (I) - during four growing seasons, between 2019 and 2022. The main goal was to assess the influence of irrigation strategies on agronomic productivity and must quality. In order to achieve this objective, a set of parameters related to vine yield and must quality was assessed. In addition, the stem water potential (SWP) was measured, and vineyard transpiration and actual evapotranspiration were estimated. The results showed clear seasonality in production, with higher productivity followed by a decline, ranging from 19 766.5 kg/ha in R 2020 to 4 726.1 kg/h in I 2021.The study demonstrated that irrigation has a favourable long-term effect on yield. This phenomenon can be ascribed to the observation that, although only numerical disparities between treatments were detected in the initial years, significant variations ($p<0.05$) were identified in 2022, between irrigation treatments. Furthermore, the DI strategy exhibited optimal water productivity, indicating high water use efficiency across the entire studied period. These findings suggest that maintenance irrigation, even in cases where it is found to be deficient, can result in enhanced water productivity in the short term, and higher productivity rates in the long-term.

RESUMO

Na região dos Vinhos Verdes, uma das castas mais cultivadas é a *Vitis vinifera* L. *cv*. 'Loureiro', produzida em condições de sequeiro. No entanto, a rega está a ser cada vez mais implementada para mitigar os efeitos das alterações climáticas. Neste sentido, no presente estudo foram avaliadas três diferentes estratégias de gestão da rega - sequeiro (R), rega deficitária (DI) e rega (I) - durante quatro ciclos culturais, entre 2019 e 2022. O principal objetivo foi avaliar a influência das estratégias de rega na produtividade agronómica e na qualidade do mosto. Para atingir este objetivo, foi avaliado um conjunto de parâmetros relacionados com o rendimento da videira e a qualidade do mosto. Além disso, foi medido o potencial hídrico do ramo (SWP) e estimada a transpiração da vinha e a sua evapotranspiração real. Os resultados mostraram uma clara sazonalidade na produção, com maior produtividade seguida de declínio, variando entre 19 766,5 kg/ha em R 2020 a 4 726,1 kg/ha em I 2021. O estudo demonstrou que a rega tem um efeito favorável a longo prazo na produtividade. Este fenómeno pode ser atribuído à constatação de que, embora apenas tenham sido detetadas disparidades numéricas entre os tratamentos nos anos iniciais, foram identificadas variações significativas ($p<0,05$) em 2022 entre as estratégias de rega. Além disso, a estratégia DI apresentou uma produtividade hídrica ótima, indicando uma elevada eficiência no uso da água durante todo o período do estudo. Estas descobertas sugerem que a rega de manutenção, mesmo nos casos em que é considerada deficitária, pode resultar numa maior produtividade hídrica a curto prazo e em taxas de produtividade elevadas a longo prazo.

Keywords: Production, grape quality, water productivity, water stress, deficit irrigation.
Palavras-chave: Produção, qualidade da uva, produtividade da água, stress hídrico, rega deficitária.

INTRODUCTION

Grapevines are cultivated across six continents in a variety of climatic conditions. The range and magnitude of environmental factors vary considerably from region to region (Schultz, 2016). The Atlantic region characterized by a temperate climate condition, has a long tradition of wine production. However, it is currently facing challenges due to climate change (Smith *et al.* 2020).

Numerous studies have focused on optimizing grapevine sustainability and productivity, exploring factors such as cover crops (Pou *et al.* 2011), disease prevention (Oliveira and Cunha, 2015; Ruano-Rosa *et al.* 2022), and soil water management (Cancela *et al.* 2016; Cataldo *et al.* 2020). These works also showed that certain cultivars of *Vitis vinifera* exhibit significant variations in production from year to year, with some producing double the yield in one year compared to other years (Blank *et al.* 2019). This seasonality is primarily influenced by climatic conditions (Ferrer-Gallego *et al.* 2012; Kizildeniz *et al.* 2015), soil water availability (Pellegrino *et al.* 2005; Ma *et al.* 2023), and cultivar characteristics (Parker *et al.* 2020; Bern *et al.* 2021). Furthermore, older plants tend to be less affected by seasonal variations (Bou Nader *et al.* 2019).

Climate change is expected to increase the frequency of droughts, intensifying water resources demand and significant agricultural challenges (Gupta *et al.* 2020). To avoid negative outcomes, such as reduced yield and lower wine quality, it is crucial to control plant water stress (Girona *et al.* 2009; Chacón-Vozmediano *et al.* 2020; Zufferey *et al.* 2020). This can be achieved by ensuring adequate water supply to plants. Anticipating future irrigation requirements is crucial to maintaining the regional identity of wine and ensuring the sustainability of the wine sector (Chrysargyris *et al.* 2020). Several approaches are taken to assess crop water status, including aerial photography for vegetation indices (Vélez *et al.* 2019; Caruso *et al.* 2023), canopy temperature analysis (Greer, 2017), photosynthetic rate measurements (Bertamini *et al.* 2006), stomatal conductance assessments (Trenti *et al.* 2021), soil water content monitoring (Zia *et al.* 2009; Gil *et al.* 2014; Cancela *et al.* 2015) and stem water potential (Munitz *et al.* 2018; Tuccio *et al.* 2019). The stem water potential is one of the most widely used and accurate indicators for assessing a crop water status (Santesteban *et al.* 2019). The authors present ranges of values to characterise the level of water stress in grapevines. These ranges are up to -0.6, between -0.6 and -0.9, -0.9 and -1.1, -1.1 and -1.4 MPa, and below -1.4 MPa, representing no stress, weak or mild stress, mild to moderate stress, moderate to severe stress, and severe stress, respectively (Leeuwen *et al.* 2009; Martínez *et al.* 2013; Miras-Avalos and Araujo, 2021). An alternative method to measure the plant water available is to assess the soil water content using equipment such as capacitive probes (Zamorano *et al.* 2021). This equipment provides information on the current soil water content, allowing to check if it is below the readily available water (Romero *et al.* 2024). If the water status is below this level, the plant will be able to continue its activity, but not at maximum performance, as it will be under water stress (Strack and Stoll, 2022).

The application of adequate irrigation at critical growth stages, mainly during the dry years, promotes a balanced vine growth, ensuring expected yields and grape quality (Junquera *et al.* 2012). Studies indicates that reducing or eliminating water stress enhances yield and berry quality attributes such as pH, probable alcohol content and titratable acidity (Acevedo-Opazo *et al.* 2010; Balint and Reynolds, 2013). However, moderate water stress can benefit wine volatile composition (Vilanova *et al.* 2019). In this sense, irrigation management should be tailored to each cultivar, and some cultivars do not justify the use of irrigation (Trigo-Córdoba *et al.* 2015), so it is essential to well characterize the cultivars to maintain high productivity rates and ensure the economic viability of the wine industry (Azorín and García, 2020; Silva *et al.* 2021a).

In the context of climate change, it is crucial to balance economic feasibility with environmental sustainability, which is becoming increasingly important (Wagner *et al.* 2023). Studies have identified targets and indicators for assessing water use in the wine grape production sector. For example, water productivity, calculated as the yield of grapes per unit of water used, has been propose (Bellvert *et al.* 2020; Er-Raki *et al.* 2021; Silva *et al.* 2024). Another approach to evaluate water use is to compare grape yield with actual transpiration or evapotranspiration of the crop obtained using models such as AquaCrop (Phogat *et al.* 2017) or SimDualKc (Paredes *et al.* 2017).

Grapevine responses to environmental conditions may vary across growing seasons. This study aimed to clarify the response of the *cv.* 'Loureiro' under different irrigation strategies over four growing seasons. Trends in yield and quality are presented over a significant period to provide reliable results. Furthermore, an additional objective was to determine the efficiency of *Vitis vinifera* L. cv 'Loureiro' production in terms of water use, using water productivity indicators.

MATERIALS AND METHODS

Site

The study was carried out in a commercial vineyard (*Vitis vinifera* L. cv 'Loureiro'), in northwest Portugal (Figure 1), during four growing seasons (2019 to 2022). The region has an Atlantic-influenced climate, characterised by high annual rainfall (>1200 mm) and relatively mild summers (Fraga *et al.* 2014). According to the Köppen–Geiger classification, it corresponds to the Csb climate type (Kottek *et al.* 2006)..

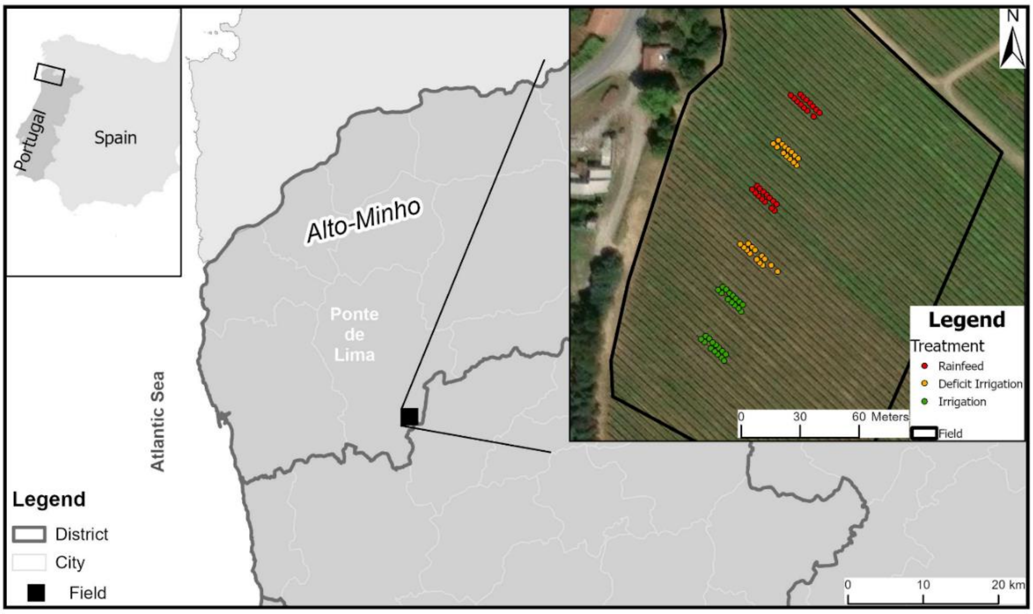

Figure 1. Study area located in northwest Portugal.

The vineyard was established in 2001, has trained to a single upward cordon training system, with a row spacing of 3.0 m and a vine spacing of 2.0 m (1666 vines/ha). The irrigation system consisted of one drip line per row, positioned 40 cm above the ground, with pressure-compensated emitters (4 L/h) spaced one meter apart.

The soil is classified as eutric regosol (WRB, 2014), with a sandy loam texture (70.2% sand, 20.3% silt, and 9.5% clay), and 1.95% organic matter. The total available soil water (TAW) at 0.8 m depth was 100 mm. The TAW was calculated by the difference between the field capacity of the soil and the permanent wilting point using eight different soil layers. To determine the field capacity, a suction of -10 kPa atmosphere was applied to the saturated soil samples using a pressure plate. A suction of -30 kPa was applied to the same samples to determine the wilting point. The field capacity and wilting point values of 0.251 cm^3/cm^3 and 0.121 cm^3/cm^3, respectively.

Climate

The meteorological data were collected from a complete weather station, which was installed on the study field, on 21 June 2018. The methodology proposed by Allen (1996) was followed to ensure the integrity of the data. Subsequently, the reference evapotranspiration (ET_o) was calculated using the FAO Penman-Monteith equation (Allen *et al.* 1998) based on this data (Equation 1). The equation is used to calculate the daily time steps.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma\,(1 - 0.34U_2)} \qquad \textbf{Eq. 1}$$

where Δ represents the slope of the saturation vapor pressure-temperature relationship at the mean air temperature (kPa/C), Rn is the net radiation at the crop surface ($MJ/m^2/d$), G is the soil heat flux density ($MJ/m^2/d$), γ is the psychometric constant (kPa/C), T is the mean daily air temperature (°C), U_2 is the wind speed (m/s) at 2 m height and ($e_s - e_a$) represents the vapour pressure at the reference height of 2 m and the deficit of air (kPa) at 2 m height.

Annual rainfall values ranged from 733 to 1646 mm in 2020 and 2022, respectively. Similar rainfall values of around 1400 mm were recorded in 2019 and 2021. The highest monthly rainfall was recorded in November 2022, at the end of this study, due to several extreme rainfall events. In all years, the highest monthly rainfall values were recorded between November and February, and the lowest between July and August (Figure 2A).

The correlation between the month and the monthly sum of ET_o is high (R^2), as shown in Figure 2B. The pattern indicates that the summer months have higher values, while the winter months have lower values in all years of this study. The highest monthly sum of 160 mm was recorded in July 2022, while the lowest monthly sum of just 14 mm was recorded in December 2021.

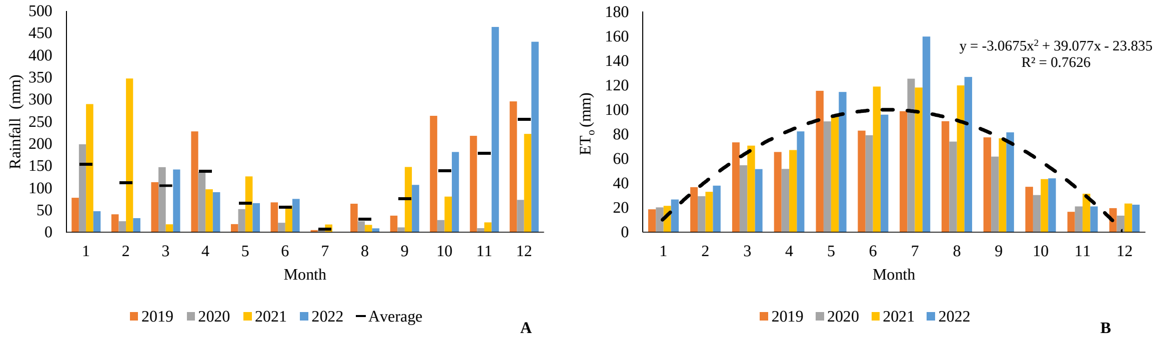

Figure 2. Monthly weather data relative to (A) Rainfall (mm/month) and (B) Reference evapotranspiration (ET_o, mm/month) for the period 2019–2022. The data were collected in a local weather station.

To characterise the climate, bioclimatic indices may be used (Cardoso *et al.* 2019). In this study, the Winkler index (WI), Huglin index (HI), Cool night index (CI), Seljaninov index (SI), and Branas index (BI) were applied. As demonstrated in Figure 2, significant variation in precipitation and ET_o values were observed throughout all growing seasons of the experiment. The application of WI and HI (Table I) revealed that in the initial year (2019), lower results were obtained compared to subsequent years. Furthermore, CI (minimum temperature) indicated that in 2022, higher minimum temperatures were recorded in September (Table I). Precipitation values fluctuated considerably during the experiment, leading to substantial variations in the indices that relate temperature to precipitation (SI and BI), also being highly divergent across the four years of the study. The year 2022 was distinguished by particularly high precipitation levels, resulting in the highest recorded values in the study (Table I).

Table I

Bioclimatic indices calculated in the years of study (2019-2022)

Index, abbreviation and author	**Results**			
	2019	**2020**	**2021**	**2022**
Winkler index (WI) (Winkler *et al.* 1974)	1771	2124	2146	1923
Huglin index (HI) (Huglin, 1978)	2847	2937	3139	2958
Cool night index (CI) (Tonietto, 1999)	8.52	6.90	8.70	9.20
Seljaninov index (SI) (Seljaninov, 1966)	0.27	0.13	0.53	0.80
Branas index (BI) (Branas *et al.* 1946)	18654	7839	14860	20227

Phenological evolution

Phenological evolution was determined using the Baggiolini scale (Baggiolini, 1952), adapted to the FAO standard crop growth stages (Table II). Therefore, the day that the vine reached stage C (green-tip bud burst) corresponds to initiation. The day the vine reached stage D (leaf emergence) corresponds to the start of the rapid growth stage. The mid-season stage corresponds to the period between phases I (flowering) and phase M (veraison). Finally, when the vine reached N (maturity), it is considered harvesting (Allen *et al.* 1998).

Table II

Day of the year (DOY) on which the vineyard growth stages were reached in the years 2019 to 2022

Crop growth stages	Growth season			
	2019	**2020**	**2021**	**2022**
Initiation (DOY)	80	61	72	88
Start rapid growth (DOY)	85	88	91	110
Start mid-season (DOY)	157	174	146	144
Start maturity (DOY)	245	233	239	241
Harvesting (DOY)	266	253	250	261
Growth season length (Days)	186	192	178	173

Stem water potential, Actual Crop Evapotranspiration, and Transpiration

The stem water potential (SWP) was measured over three growing seasons (2019, 2020, and 2021), using a Scholander pressure chamber (model 670, PMS Instrument Company, OR, USA). To obtain these readings, a mature and healthy leaf from plants 3 and 5 of the central rows (8 replications per treatment and sampling date) was enclosed in an opaque, aluminium-lined bag one hour before solar noon. At solar noon, the leaf was excised from the plant, and SWP readings were recorded (Choné *et al.* 2001).

To obtain actual crop evapotranspiration ($ET_{c\ act}$) and transpiration (T) throughout the growing season, the dual crop coefficient approach (Allen *et al.* 1998) was applied using the SimDualKc software (Rosa *et al.* 2012) with the recommended parameters for *Vitis vinifera cv.* 'Loureiro' (Silva *et al.* 2021b). The basal crop coefficients values ($K_{cb\ full\ ini}$, $K_{cb\ full\ mid}$, and $K_{cb\ full\ end}$) used were 0.33, 0.79 and 0.60, respectively, and depletion fraction values (p_{ini}, p_{mid} and p_{end}) were 0.45, 0.54 and 0.45, respectively.

Irrigation treatments

In this study, two irrigation treatments were considered: Irrigation (I), determined by the vine grower, and deficit irrigation (DI) which ranged between 25 and 40%, depending on water availability for irrigation. Additionally, a rainfed treatment (R), the most common in the region, was included. Each treatment had two replicates, with each replicate consisting of four rows. The two central rows were used to evaluate all parameters, while the two additional rows were used as buffers. The depth and number of irrigations in each growing season are shown in Table III.

Table III

Irrigation data: depths, numbers and DOY start and end of observed irrigation events, between 2019 and 2022

Year	Total depth irrigation (mm)		Number of irrigations		DOY started	DOY end
	DI	**I**	**DI**	**I**		
2019	17.33	69.67	2	10	142	238
2020	32.00	94.00	6	10	181	239
2021	10.66	39.99	2	4	210	243
2022	21.33	53.33	3	5	207	235

DOY= day of year; DI= deficit irrigation; I = irrigation.

Production, must quality, and water productivity

The study analysed production parameters related to the number of bunches per plant, production per plant (kg) to determine yield (t/h). In addition, qualitative parameters, such as the weight of 100 berries (g), pH, probable alcohol (%), and titratable acidity (g/L tartaric acid eq.) were obtained.

A total of 28 vines were individually harvested per treatment, resulting in a total of 84 vines. The harvested bunches from each plant were counted and then placed in a container. A portable digital scale (model SD-0206, SANDA, China) was used to weigh the samples, with a maximum deviation of 5g between 0-10kg.

Following weighing, sample bunches of the plant (approximately two kg per repetition) were taken and stored in insulated containers with ice packs, for subsequent laboratory analysis.

In the laboratory, 100 randomly selected berries from each sample were weighed using an electronic balance with a maximum error of 0.01g. The samples were then crushed, and the soluble solids (° Brix) were measured using a digital refractometer (PEN-PRO 3730, ATAGO, Japan), which was converted to probable alcohol (%). pH and titratable acidity (g/L) were also measured, with acidity determined by the amount of NaOH (mL) using the semiautomatic titrator (PH-Burette 24, CRISON, Spain). The procedures were carried out over a four-year period, except for 2020 when laboratory tests were not possible due to pandemic-related constraints (COVID-19).

In this study, the concept of water productivity is based on the correlation between grape yield (GY) and three parameters: total water use (TWU), transpiration (T), and current crop evapotranspiration ($ET_{c\ act}$), using Equations 2, 3 and 4. The TWU represents the total water used during the production cycle and was calculated by adding precipitation, irrigation, and the variation in soil water content over the growing season. The T and $ET_{c\ act}$ were determined using the SimDualKc results (Silva *et al.* 2021b).

$$WP_{TWU} = \frac{GY}{TWU} \quad \textbf{Eq. 2}$$

$$WP_{T} = \frac{GY}{T} \quad \textbf{Eq. 3}$$

$$WP_{ET} = \frac{GY}{ET_{c\ act}} \quad \textbf{Eq. 4}$$

where TWU corresponds to the water used (which includes rainfall, soil water storage, capillary rise and irrigation applied,), GY refers to achieve grape yielded (Kg/ha), T refers to transpiration (crop plus ground cover, m^3/ha) and $ET_{c\ act}$ is actual crop evapotranspiration (m^3/ha).

Statistical analysis

To analyse the variability of treatment means and perform post hoc comparisons, a one-way ANOVA was conducted using in SPSS 27. The post hoc tests were performed using Duncan's test with a significance level of $p < 0.05$.

RESULTS AND DISCUSSION

Climate during growing seasons

The impact of climatic factors on viticulture is a well-documented phenomenon, with variables such as temperature, relative humidity, wind speed and reference evapotranspiration (ET_o) directly influencing vine development and grape quality (Prada *et al.* 2024). Data obtained from the meteorological station installed on site revealed significant variations in the average annual temperature throughout the growing seasons. Specifically, in 2019, the mean temperature was recorded at 18.2 °C, with a minimum of 6.8 °C (DOY 94) and a maximum of 27.1 °C (DOY 192). In 2020, a decline was observed to 17.3 °C, with no significant alteration in the extreme values observed in the preceding year. In 2021, the average temperature increased slightly to 17.6 °C, with a slight rise in extreme values, ranging from a minimum of 9.4 °C (DOY 72) to a maximum of 27.4 °C (DOY 235). A significant increase in the average temperature was observed in 2022 to 19.1 °C, with a maximum peak of 30.8 °C (DOY 193). The progressive rise in average temperatures, especially in 2022, suggests an impact on the phenological cycle of the vines, including accelerated ripening (Dinis *et al.* 2022), leading to a shorter growing season (Table II).

The mean relative humidity exhibited minimal variability, fluctuating from 73.80% in 2019 to 78.72% in 2021. However, the minimum values demonstrated greater variation. The years 2020 and 2022 were characterised by the lowest relative humidity levels, with minimum values of 51% (DOY 196) and 50% (DOY 231), respectively. Regarding the wind in 2019, the average speed was recorded at 1.12 m/s, while in 2020, it experienced a decline to 1.05 m/s. In the subsequent years, a steady increase was observed, with 1.51 m/s in 2021 and 1.59 m/s in 2022. A significant variation in growing seasons precipitation was observed between 2019 and 2022, with 2019 recording the highest accumulation (394 mm) and 2021 the lowest (323 mm). Furthermore, 2022 was distinguished by its high number of rainy days (81), in contrast to 2019 and 2020, which recorded only 55 days with precipitation. It was also observed that the greatest rainfall tends to occur at the beginning of the harvest.

A significant increase in the average ET_o was observed during the growing seasons (Figure 2). Specifically, the average recorded in 2019 was 2.99 mm/day, which decreased to 2.60 mm/day in 2020. Subsequent years witnessed a marked increase, reaching 3.36 mm/day in 2021 and 3.60 mm/day in 2022. This increase in ET_o can be attributed to an increased water demand by plants, particularly in 2022, when a combination of high temperature and high ET_o.

The results indicate that the years analysed presented distinct climatic conditions, with emphasis on the increase in average temperature and ET_o in 2022, bringing forward the harvest by 16 days, compared to the average in years 2019 and 2020.

Such climatic changes are likely to impact viticulture, reducing the days of vegetative growth (Table II), vine metabolism and quality of the grapes (Cunha *et al.* 2020; Dinis *et al.* 2022).

Stem Water Potential, Actual Crop Evapotranspiration, and Transpiration

Figure 3 shows the SWP in three growing seasons. It is evident that there are no significant differences between treatments in the same DOY (Figure 3.A.1., B.1. and C.1.). However, the values achieved by irrigation treatment are slightly better than those of the other treatments in most DOYs. This fact is reflected where the mean SWP for treatments during the entire season shows differences between treatments (Figure 3.A.2., B.2. and C.2.).

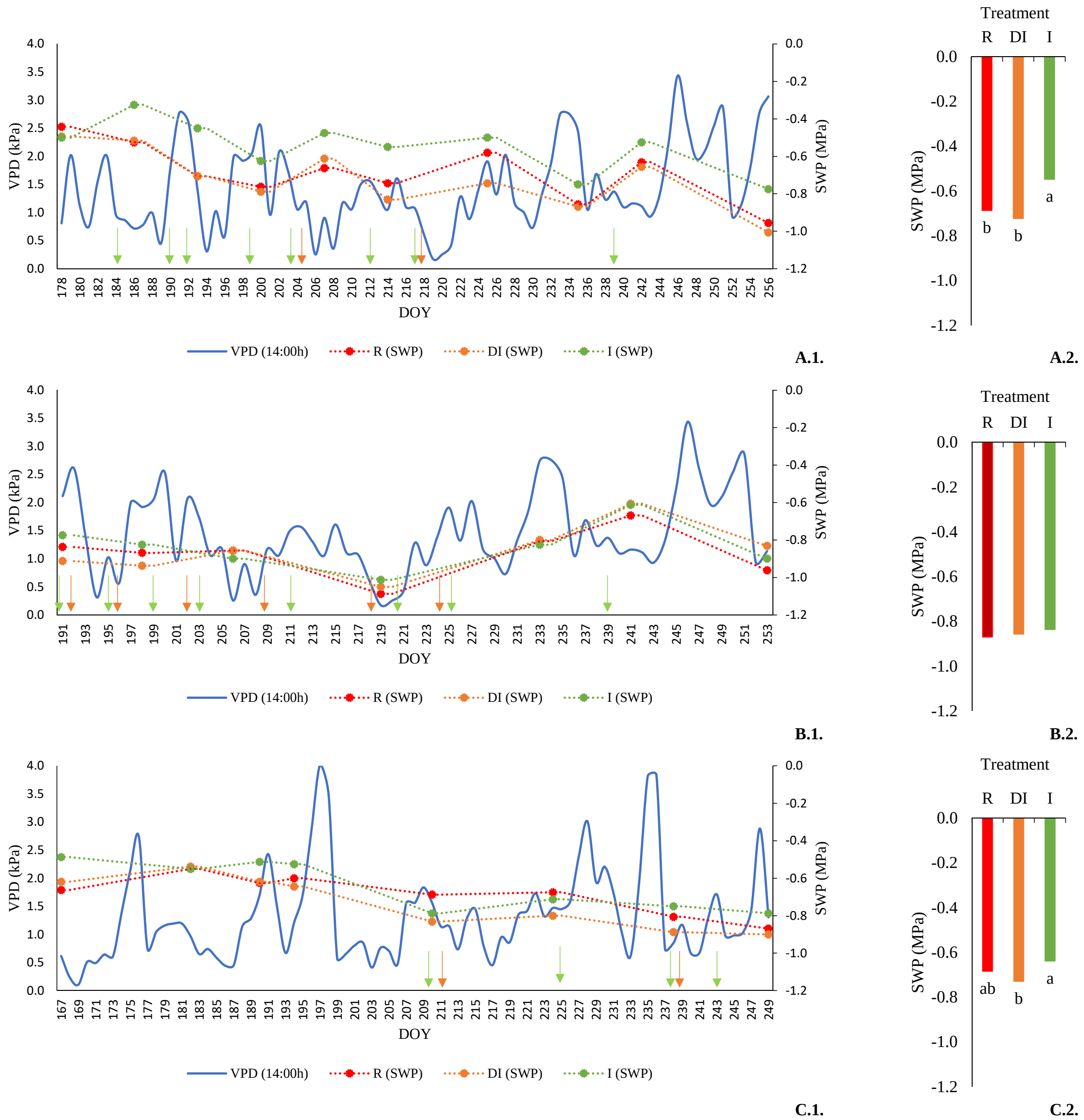

Figure 3. Vapor pressure deficit (VPD) at 14:00 (solar noon) and stem water potential (SWP, MPa) for control treatments (R), deficit irrigation (DI), and irrigation (I) measured during the growing seasons 2019 (A), 2020 (B) and 2021 (C) for the evolution of SWP during the season (1) and the mean SWP for each season (2). Arrows indicate irrigation moments for DI (↓) and I (↓) treatments. Different letters indicate a significant difference between groups with $p < 0.05$, using one-way ANOVA followed by Duncan's post hoc test.

As previously documented by other researchers (Williams and Baeza, 2007), the SWP (Figure 3) exhibited a notable response to prevailing climatic conditions. Despite the observed variations among the treatments, these differences did not attain statistical significance across any of the designated DOY as other authors had already reported (Santesteban *et al.* 2011, 2019). According to Leeuwen *et al.* (2009), the vineyard was mostly subjected to no stress or weak to mild stress, with occasional instances of moderate to severe stress (Figure 3A). This finding is consistent with the results reported by Gil *et al.* (2014) and Cole and Pagay (2015), who also occasionally recorded values lower than -1.2 MPa. Although no noticeable differences were observed when analysing the set of dates, significant differences were found between the treatments in 2019 and 2021 (Figure 3B).

Strategy I exhibited better results (lower SWP) than the other treatments, as previously described by Martínez *et al.* (2013). Considering all growing seasons, differences were found between the DOY (Figure 3A). In 2019 and 2021 the SWP values gradually decreased throughout the growing season, as reported in several previous references (Olivo *et al.* 2009). Nevertheless, in 2020, a decline in stress conditions, lower VDP and ETo values in the middle phase resulted in a subsequent decrease in SWP values in this phase, as described by Morabito *et al.* (2022) that suitable conditions can rapidly increase the SWP. The analysis of Figure 3A also, suggests a strong direct relationship between SWP and VDP as the lowest SWP readings were recorded a few days after periods of higher VPD readings are obtained days after the occurrence of higher VDP.

Regarding the values obtained for actual crop evapotranspiration and transpiration, significant differences were observed between treatments and crop years (Table IV). In 2020, treatment R had the lowest $ET_{c\ act}$ and transpiration values, whereas in 2022 treatment I recorded the highest values for these indicators (Table IV). In this sense, the results obtained using SIMDualKc enabled a precise assessment of the differences between the values of $ET_{c\ act}$ (mm) and transpiration (mm) across treatments and seasons (Table IV). Regarding the $ET_{c\ act}$, values ranged from 269 mm (R-2020) to 396 mm (I-2022). Similarly, transpiration showed considerable variation, with values ranging from 140 mm (R-2020) to 241 mm (I-2022). Such differences have already been reported in vineyards, with a about 52% and about 42% difference between the extreme values in $ET_{c\ act}$ (mm) and Transpiration (mm), respectively (Fandiño, 2021), similar results have also been reported for the olive (Paço *et al.* 2019; Puig-Sirera *et al.* 2021).

Table IV

Actual crop evapotranspiration and transpiration for four years (2019 to 2022 obtained using SIMDualKc

Year	Treatment	$ET_{c\ act}$ (mm)	Transpiration (mm)
	R	325	198
2019	DI	336	207
	I	359	216
	R	269	140
2020	DI	291	154
	I	306	163
	R	365	219
2021	DI	371	222
	I	385	234
	R	361	207
2022	DI	372	229
	I	396	241

Where: $ET_{c\ act}$ represents actual crop evapotranspiration in mm, R is control treatment, DI is deficit irrigation treatment and I correspond to irrigation treatment.

Production and Quality

Regarding the qualitative and quantitative parameters resulting from the treatments, it was found that there were no significant differences between the treatments under the same climatic conditions. The observed differences were related to the number of bunches per vine in 2019, the fresh mass of 100 berries in 2020 and 2022, and the yield in 2022 (Table V). However, over the years with different irrigation treatments, there was a slight tendency for higher irrigation levels to increase yield, number of bunches per vine, fresh berry mass, pH, and total acidity. In contrast, higher irrigation led to lower probable alcohol (Table V).

The absence of differences in production parameters between irrigation treatments is consistent with the findings described for the *cv.* 'Godello' (Trigo-Córdoba *et al.* 2015) and *cv.* 'Chardonnay' (Ma *et al.* 2023). However, in 2022, treatment I yielded approximately 54% more than treatment R, indicating significant differences in that year (Table V). This behaviour was not only due to the irrigation applied in that year, but also to the influence of continuous irrigation during previous years (Munitz *et al.* 2017). Table V shows a progressive increase in the difference in yield between treatments R and I over the years, culminating in 2022 with a higher yield. This trend aligns with previous studies on *cv.* 'Monastrell' (Romero *et al.* 2016) and *cv.* 'Cabernet Sauvignon' (Junquera *et al.* 2012), in which long-term irrigation treatments caused differences in yield and other parameters. In 2019, additional differences were observed in bunches per vine (Table V), where treatment I recorded the highest mean value ($P < 0.05$). Additionally, in two years, the fresh mass of the berries was higher in treatment I compared to treatment R (Table V), in agreement with reporting for *cv.* 'Verdejo' (Vilanova *et al.* 2019). However, no significant differences were found between treatments in qualitative parameters, such as pH, probable alcohol, and titratable acidity (Table V), similar to what was reported for *cv.* 'Albariño' and *cv.* 'Godello' (Cancela *et al.* 2016). Therefore, it is possible to conclude that irrigation did not influence the quality parameters in this cultivar under the given climatic conditions. In contrast, irrigation was found to decrease probable alcohol content in *cv.* 'Cabernet Sauvignon' (Acevedo-Opazo *et al.* 2010) and increase titratable acidity (Junquera *et al.* 2012), with no differences in pH in either study.

Table V

Production and quality parameters related all five growing seasons (2019 to 2022) in different treatments.

Year	Treatment	Yield (t/ha)	Bunches per vine	Fresh mass of 100 berries (g)	pH	Probable alcohol (%)	Titratable acidity (g/L tartaric acid eq.)
2019	R	9.87	32.04^{b}	191.67	3.07	10.89	7.90
	DI	12.04	38.00^{ab}	184.14	2.99	10.79	7.25
	I	13.13	42.82^{a}	196.29	2.98	10.18	8.31
2020	R	19.77	51.21	163.09^{a}	-	-	-
	DI	20.28	52.50	181.47^{b}	-	-	-
	I	22.89	62.04	191.06^{b}	-	-	-
2021	R	4.72	14.29	192.08	2.83	10.80	7.27
	DI	6.52	18.50	203.64	2.84	11.20	7.32
	I	7.23	19.14	207.78	2.90	11.30	8.28
2022	R	12.57^{b}	30.79	163.25^{a}	3.01	10.06	7.64
	DI	16.85^{ab}	40.07	177.66^{ab}	3.01	10.25	7.82
	I	19.36^{a}	41.33	188.66^{b}	3.12	10.63	7.88

Different letters indicate a significant difference between groups with $p < 0.05$, using one-way ANOVA followed by Duncan's post hoc test. R= control, DI= deficit irrigation; I = irrigation.

Although no differences were observed between treatments, there were significant differences between the growing seasons. Seasonal variation can be observed in the parameters such as yield, bunches per vine and fresh mass of 100 berries. The interannual variation in production and quality is shown in Figure 4. However, the average yield was 14.66 t/ha, a value similar to that reported by Oliveira *et al.* (2020) for healthy plants of the *cv.* 'Loureiro'. As demonstrated in Figure 4, there is a clear indication of interannual variability in the yield, bunches per vine, and fresh berry mass in this study. Yield ranged from 6.16 t/ha (in 2021) and 20.98 t/ha (in 2020), bunches per vine between approximately 17 (in 2021) and 55 (in 2020), and fresh mass of 100 berries between 179 g (in 2021) and 201 g (in 2020). In this sense, there is a clear seasonality effect since years with high production are preceded by years with significantly lower values (Figure 4A). Similar trend has been reported in the Douro region (Cunha and Richter, 2012) and in other cultivars such as *cv.* 'Tempranillo' (Intrigliolo and Castel, 2009) and *cv.* 'Merlot' (Chacón-Vozmediano *et al.* 2020). On average, the pH, probable alcohol, and titratable acidity values were 2.97, 10.68%, and 7.74 g/L, respectively (Figure 4 D, E, F). Nevertheless, significant fluctuations were observed over the years. These fluctuations have also been reported in other studies with different grape varieties (Balint and Reynolds, 2013; Romero *et al.* 2016). These findings underscore the importance of considering water productivity when planning the irrigation strategy for vineyard (Junquera *et al.* 2012), as proposed in the next section.

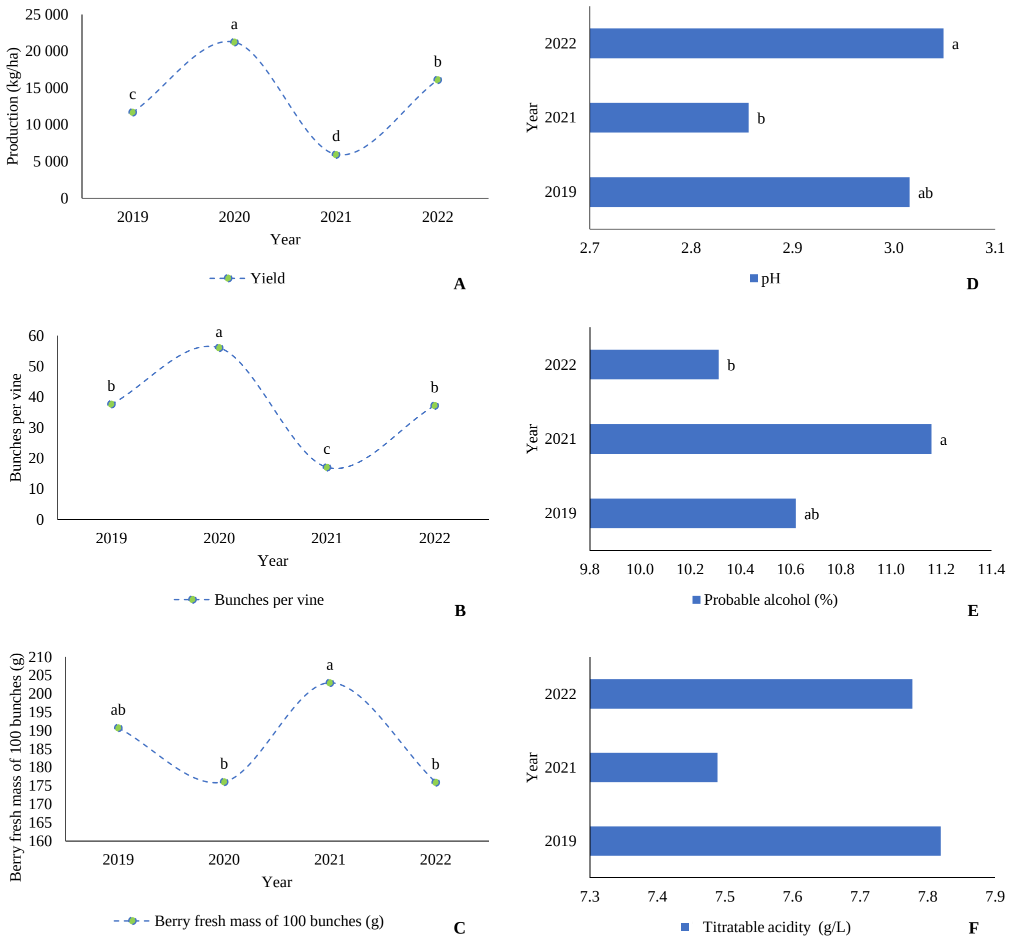

Figure 4. Yield (**A**), bunches per vine (**B**), fresh mass of 100 berries (g) (**C**), pH (**D**), probable alcohol (**E**) and titratable acidity (**F**) related all four growing seasons (2019 to 2022). Different letters indicate a significant difference between groups with $p < 0.05$, using one-way ANOVA followed by Duncan's post hoc test.

Water Productivity

The results of the water productivity calculations are presented in Table VI. Significant differences were found between treatments R, DI, and I in all years except 2021. Additionally, DI treatment consistently produced the best results, although it did not always have the highest numerical values, since it consistently showed values without significant differences. Treatment I only showed significantly better values than the control treatment in 2022, regardless of the parameter.

It is evident that the most beneficial irrigation strategy is DI, because regardless of the year, the WP in the DI strategy always generates the best result (Table VI). This finding aligns with the results reported by other authors (Shellie, 2014; Ma *et al.* 2023). However, it is important to note that WP can vary depending on the location and cultivar. For example, in Italy with *cv.* 'Cannonau', some authors found that lower irrigation levels can lead to higher WP values (Oliveira *et al.* 2013). The highest values of the WP_{GY}, WP_T and $WP_{ETc\ act}$ were recorded in DI-2020, where 4.73, 7.87 and 14.89 kg/m^3 were obtained, respectively. On the contrary, the lowest values of these same indicators were recorded in DI-2021, at 1.07, 1.27 and 2.13 kg/m^3, respectively (Table VI). These values varied greatly over the years (Table VI and Figure 5), and were strongly influenced by the variation in grape yield (GY) (Figure 4). Thus, Figure 5 shows a similar trend to that reported in production: a high WP value is preceded by a significantly lower one. Significant variations in WP have also been reported for *cv.* 'Albariño' (Mirás-Avalos *et al.* 2016), but they were less pronounced than those recorded in this work. It should be noted that the $WP_{ETc\ act}$ in 2020 stands out as a strange value compared to all other values obtained in this study, as well as those presented by Phogat *et al.* (2017), who obtained values of approximately 6 kg/m^3. This anomaly is ascribed to the exceptionally high productivity observed in 2020 compared to the other years in the study.

Table VI

Mean of water productivity (WP) in function grape yield (GY), transpiration (T), and actual crop evapotranspiration ($ET_{c\ act}$) and, related for four growing seasons (2019 to 2022) in different treatments

Year	Treatment	WP_{GY} (kg/m^3)	WP_T (kg/m^3)	$WP_{ETc\ act}$ (kg/m^3)
2019	R	2.76 ± 0.30^a	4.04 ± 0.44^a	6.65 ± 0.72^a
	DI	2.39 ± 0.20^{ab}	3.58 ± 0.30^{ab}	5.83 ± 0.49^{ab}
	I	1.76 ± 0.19^b	2.75 ± 0.30^b	4.58 ± 0.50^b
2020	R	4.39 ± 0.34^a	7.53 ± 0.58	14.52 ± 1.12
	DI	4.73 ± 0.32^a	7.87 ± 0.54	14.89 ± 1.02
	I	3.11 ± 0.40^b	6.45 ± 0.83	12.09 ± 1.55
2021	R	1.50 ± 0.17	1.79 ± 0.21	2.98 ± 0.35
	DI	1.07 ± 0.14	1.27 ± 0.17	2.13 ± 0.29
	I	1.59 ± 0.28	1.88 ± 0.33	3.09 ± 0.54
2022	R	3.22 ± 0.41^b	3.49 ± 0.44^b	6.07 ± 0.77^b
	DI	4.20 ± 0.31^{ab}	4.54 ± 0.33^{ab}	7.36 ± 0.54^{ab}
	I	4.55 ± 0.32^a	4.89 ± 0.34^a	8.02 ± 0.57^a

Different letters indicate a significant difference between groups with $p < 0.05$, using one-way ANOVA followed by Duncan's post hoc test. ± represents the Standard error. R= control, DI= deficit irrigation; I = irrigation.

Comparing the years, 2020 had the best values for all WP parameters, while the following year (2021) showed the lowest values (Figure 5). The pattern observed indicates interannual oscillation in this parameter: years with high values tend to be both preceded and followed by years with lower values, similar to the behaviour documented for production.

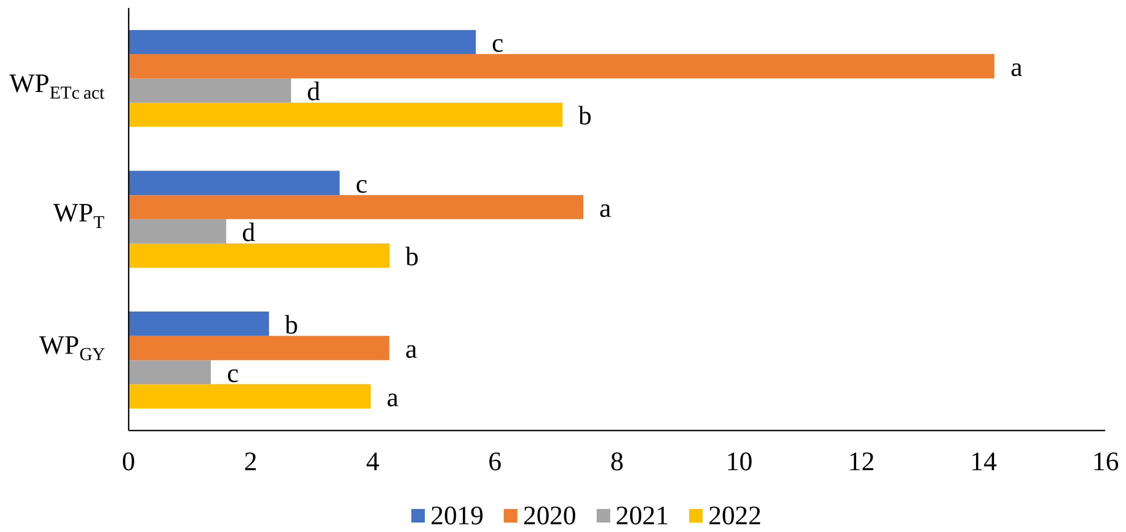

Figure 5 Variation in water productivity (WP) in function of grape yield (GY), Transpiration (T) and actual crop evapotranspiration ($ET_{c\ act}$) during four growing seasons (2019 to 2022). Different letters indicate a significant difference between groups with $p < 0.05$, using one-way ANOVA followed by Duncan's post hoc test.

CONCLUSIONS

During the growing cycle *cv.* 'Loureiro', variations in stem water productivity were observed over time. However, irrigation strategies did not result in significant differences when comparing measurements taken on the same date. Additionally, the plants were rarely subjected to moderate or severe stress in all treatments.

Similarly, no significant differences in annual productivity and quality were observed between treatments during the first three years. However, in the last year, such differences emerged, indicating that accumulated water stress over several years could lead to reduced productivity under rainfed conditions.

Additionally, the present study demonstrated a clear annual fluctuation in yield, along with substantial variations in the number of bunches per plant and grape weight. These fluctuations were evident over time, with years of high production often succeeded by years of low production.

Based on water productivity indicators, the DI strategy has consistently proven to be the most efficient. Therefore, it is recommended to apply this strategy in the region for this cultivar. This approach ensures superior production efficiency without compromising grape yield and quality.

Future studies should further investigate the observed seasonal variability in productivity and assess whether deficient irrigation strategies remain beneficial in the context of climate change.

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REFERENCES

Acevedo-Opazo C., Ortega-Farias 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. *Agric. Water Manag.,* **97**, 956–964.

Allen R.G., 1996. Assessing Integrity of Weather Data for Reference Evapotranspiration Estimation. *J. Irrig. Drain Eng.,* **122**, 97–106.

Allen R.G., Pereira L.S., Smith M., Raes D., 1998. Crop Evapotranspiration. Guide- lines for Computing Crop Water Requirements. *FAO Irrig. Drain Pap.,* **56**, 300.

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. *Sustain,* **12,** 1930.

Baggiolini M., 1952. Les stades repères dans le développement annuel de la vigne et leur utilisation pratique. *Revue romande d'Agriculture et d'Arboriculture,* **8**, 4–6

Balint G., Reynolds A.G., 2013. Effect of different irrigation strategies on vine physiology, yield, grape composition and sensory profile of Sauvignon blanc (*Vitis vinifera* L.) in a cool climate area. *J. Int. des Sci. la Vigne du Vin,* **47**, 159–181.

Bellvert J., Mata M., Vallverdú X., Paris C., Marsal J., 2020. Optimizing precision irrigation of a vineyard to improve water use efficiency and profitability by using a decision-oriented vine water consumption model. *Precis. Agric.,* **22**, 319–341.

Bernáth S., Paulen O., Šiška B., Kus Z., František T., 2021. Influence of Climate Warming on Grapevine (Vitis vinifera L .) Phenology in Conditions of Central Europe (Slovakia). *Plants,* **10**, 1020.

Bertamini M., Zulini L., Muthuchelian K., Nedunchezhian N., 2006. Effect of water deficit on photosynthetic and other physiological responses in grapevine (*Vitis vinifera* L. *cv.* Riesling) plants. *Photosynthetica,* **44**,151–154.

Blank M., Hofmann M., Stoll M., 2019. Seasonal differences in Vitis vinifera L. *cv.* Pinot noir fruit and wine quality in relation to climate. *OENO One*, **53 189-203**.

Bou Nader K., Stoll M., Rauhut D., Patz C.D., Jung R., Loehnertz O., Schultz H.R., Hilbert G., Renaud C., Roby J.P., 2019. Impact of grapevine age on water status and productivity of *Vitis vinifera* L. *cv.* Riesling. *Eur. J. Agron.,* **104**, 1–12.

Branas J., Bernon G., Levadoux L., 1946. Eléments de viticulture générale. 400pp. École National d'Agriculture de Montpellier.

Cancela J.J., Fandiño M., Rey B.J., Martínez E.M., 2015. Automatic irrigation system based on dual crop coefficient, soil and plant water status for Vitis vinifera (cv Godello and cv Mencía). *Agric. Water Manag.,* **151**,52–63.

Cancela J.J., Trigo-Córdoba E., Martínez E.M., Rey B.J., Bouzas-Cid Y., Fandiño M., Mirás-Avalos J.M., 2016. Effects of climate variability on irrigation scheduling in white varieties of *Vitis vinifera* (L.) of NW Spain. *Agric. Water Manag.,* **170**, 99–109.

Cardoso A.S., Alonso J., Rodrigues A.S., Araújo-Paredes C., Mendes S., Valín M.I., 2019. Agro-ecological terroir units in the North West Iberian Peninsula wine regions. *Appl. Geogr.,* **107**, 51–62.

Caruso G., Palai G., Tozzini L., D'Onofrio C., Gucci R., 2023. The role of LAI and leaf chlorophyll on NDVI estimated by UAV in grapevine canopies. *Sci. Hortic.* (Amsterdam), **322**, 112398.

Cataldo E., Salvi L., Sbraci S., Storchi P., Mattii G.B., 2020. Sustainable Viticulture: Effects of Soil Management in Vitis vinifera. *Agronomy,* **10,** 1949.

Chacón-Vozmediano J.L., Martínez-Gascueña J., García-Navarro F.J., Jiménez-Ballesta R., 2020. Effects of water stress on vegetative growth and 'Merlot' grapevine yield in a semi-arid mediterranean climate. *Horticulturae,* **6,** 95.

Choné X., Van Leeuwen C., Dubourdieu D., Gaudillère J.P., 2001. Stem water potential is a sensitive indicator of grapevine water status. *Ann. Bot.,* **87,** 477–483.

Chrysargyris A., Xylia P., Litskas V., Stavrinides M., Heyman L., Demeestere K., Höfte M., Tzortzakis N., 2020. Assessing the impact of drought stress and soil cultivation in Chardonnay and Xynisteri grape cultivars. *Agronomy,* **10,** 670.

Cole J., Pagay V., 2015. Usefulness of early morning stem water potential as a sensitive indicator of water status of deficit-irrigated grapevines (*Vitis vinifera* L.). *Sci. Hortic.* (Amsterdam), **191**, 10–14.

Cunha M., Richter C., 2012. Measuring the impact of temperature changes on the wine production in the Douro Region using the short time fourier transform. *Int. J. Biometeorol,* **56**, 357–370.

Cunha M., Richter C., Mario C., Christian R., 2020. Climate-induced cyclical properties of regional wine production using a time-frequency approach in douro and minho wine regions. *Ciência Téc. Vitiv.,* **35**, 16–29.

Dinis L.T., Bernardo S., Yang C.Y., Fraga H., Malheiro A.C., Moutinho-Pereira J., Santos J.A., 2022. Mediterranean viticulture in the context of climate change. *Ciência Téc. Vitiv.*, **37**, 139–158.

Er-Raki S., Bouras E., Rodriguez J.C., Watts C.J., Lizarraga-Celaya C., Chehbouni A., 2021. Parameterization of the AquaCrop model for simulating table grapes growth and water productivity in an arid region of Mexico. *Agric. Water Manag.,* **245**, 106585.

Fandiño M., 2021. *Necesidades de Agua e influencia de los sistemas de riego en Vitis vinifera var.* Albariño. 153 p. PhD Thesis, Escuela De Doctorado Internacional De La Universidad De Santiago De Compostela.

Ferrer-Gallego R., Hernández-Hierro J.M., Rivas-Gonzalo J.C., Escribano-Bailón M.T., 2012. Influence of climatic conditions on the phenolic composition of *Vitis vinifera* L. *cv.* Graciano. *Anal. Chim. Acta,* **732**, 73–77.

Fraga H., Malheiro A.C., Moutinho-Pereira J., Santos J.A., 2014. Climate factors driving wine production in the Portuguese Minho region. *Agric. For. Meteorol.,* **185**, 26–36.

Gil P.M., Saavedra J., Schaffer B., Navarro R., Fuentealba C., Minoletti F., 2014. Quantifying effects of irrigation and soil water content on electrical potentials in grapevines (*Vitis vinifera*) using multivariate statistical methods. *Sci. Hortic.* (Amsterdam), **173**, 71–78.

Girona J., Marsal J., Mata M., Del Campo J., Basile B., 2009. Phenological sensitivity of berry growth and composition of tempranillo grapevines (*Vitis vinifera* L.) to water stress. *Aust. J. Grape Wine Res.,* **15**, 268–277.

Greer D.H., 2017. Responses of biomass accumulation, photosynthesis and the net carbon budget to high canopy temperatures of *Vitis vinifera* L. *cv.* Semillon vines grown in field conditions. *Environ. Exp. Bot.,* **138**, 10–20.

Gupta A., Rico-Medina A., Caño-Delgado A.I., 2020. The physiology of plant responses to drought. *Science,* **368**, 266–269.

Huglin P., 1978. Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. *Comptes Rendus l'Académie d'Agriculture deFrance*, **64**, 1117–1126.

Intrigliolo D.S., Castel J.R., 2009. Response of *Vitis vinifera cv.* "Tempranillo" to partial rootzone drying in the field: Water relations, growth, yield and fruit and wine quality. *Agric. Water Manag.*, **96**, 282–292.

Junquera P., Lissarrague J.R., Jiménez L., Linares R., Baeza P., 2012. Long-term effects of different irrigation strategies on yield components, vine vigour, and grape composition in *cv.* Cabernet-Sauvignon (*Vitis vinifera* L.). *Irrig. Sci.*, **30,** 351–361.

Kizildeniz T., Mekni I., Santesteban H., Pascual I., Morales F., Irigoyen J.J., 2015. Effects of climate change including elevated CO2 concentration, temperature and water deficit on growth, water status, and yield quality of grapevine (*Vitis vinifera* L.) cultivars. *Agric. Water Manag.*, **159**, 155–164.

Kottek M., Grieser J., Beck C., Rudolf B., Rubel F., 2006. World map of the Köppen-Geiger climate classification updated. *Meteorol. Zeitschrift*, **15**, 259–263.

Leeuwen V., Tregoat O., Choné X., Bois B., Pernet D., Gaudillére J.P., 2009. Vine water status is a key factor in grape ripening and vintage quality for red bordeaux wine. How can it be assessed for vineyard management purposes? *J. Int. des Sci. la Vigne du Vin* **43,** 121–134.

Ma X., Han F., Wu J., Ma Y., Jacoby P.W., 2023. Optimizing crop water productivity and altering root distribution of Chardonnay grapevine (*Vitis vinifera* L.) in a silt loam soil through direct root-zone deficit irrigation. *Agric. Water. Manag.*, **277**, 108072.

Martínez E.M., Rey B.J., Fandiño M., Cancela J.J., 2013. Comparison of two techniques for measuring leaf water potential in *Vitis vinifera* var. Albariño. *Ciência Téc. Vitiv.*, **28**, 29–41.

Miras-Avalos J.M., Araujo E.S., 2021. Optimization of vineyard water management: Challenges, strategies, and perspectives. *Water* (Switzerland), **13**, 746.

Mirás-Avalos J.M., Trigo-Córdoba E., Bouzas-Cid Y., Orriols-Fernández I., 2016. Irrigation effects on the performance of grapevine (*Vitis vinifera* L.) *cv.* "Albarino" under the humid climate of galicia. *OENO One*, **50**, 183–194.

Morabito C., Orozco J., Tonel G., Cavalletto S., Meloni G.R., Schubert A., Gullino M.L., Zwieniecki M.A., Secchi F., 2022. Do the ends justify the means? Impact of drought progression rate on stress response and recovery in Vitis vinifera. *Physiol. Plant,* **174,** e13590 .

Munitz S., Netzer Y., Schwartz A., 2017. Sustained and regulated deficit irrigation of field-grown Merlot grapevines. *Aust. J. Grape Wine Res.*, **23,** 87–94.

Munitz S., Netzer Y., Shtein I., Schwartz A., 2018. Water availability dynamics have long-term effects on mature stem structure in *Vitis vinifera*. *Am. J. Bot.*, **105**, 1443–1452.

Oliveira A.F., Mameli M.G., Pau L., Satta D., Nieddu G., 2013. Deficit irrigation strategies in vitis vinifera L. *cv.* Cannonau under mediterranean climate. Part II - cluster microclimate and anthocyanin accumulation patterns. *South African J. Enol. Vitic.*, **34,** 184–195.

Oliveira M., Cunha M., 2015. Study of the Portuguese populations of powdery mildew fungus from diverse grapevine cultivars (*Vitis vinifera*). *J. Int. des Sci. la Vigne du Vin.*, **49**, 173–182.

Oliveira M.J.R.A., Castro S., Paltrinieri S., Bertaccini A., Sottomayor M., Santos C.S., Vasconcelos M.W., Carvalho S.M.P., 2020. "Flavescence dorée" impacts growth, productivity and ultrastructure of *Vitis vinifera* plants in Portuguese "Vinhos Verdes" region. *Sci. Hortic.* (Amsterdam), **261**, 108742.

Olivo N., Girona J., Marsal J., 2009. Seasonal sensitivity of stem water potential to vapour pressure deficit in grapevine. *Irrig. Sci.*, **27,** 175–182.

Paço T.A., Paredes P., Pereira L.S., Silvestre J., Santos F.L., 2019. Crop coefficients and transpiration of a super intensive Arbequina olive orchard using the dual Kc approach and the Kcb computation with the fraction of ground cover and height. *Water* (Switzerland)**,** **11**, 383.

Paredes P., Rodrigues G.C., Cameira M. R., Torres M.O., Pereira L.S., 2017. Assessing yield, water productivity and farm economic returns of malt barley as influenced by the sowing dates and supplemental irrigation. *Agric. Water Manag.*, **179**, 132–143.

Parker A.K., García de Cortázar-Atauri I., Gény L., Spring J.L., Destrac A., Schultz H., Molitor D., Lacombe T., Graça A., Monamy C., 2020. Temperature-based grapevine sugar ripeness modelling for a wide range of *Vitis vinifera* L. cultivars. *Agric. For. Meteorol.*, **285–286**, 107902.

Pellegrino A., Lebon E., Voltz M., Wery J., 2005. Relationships between plant and soil water status in vine (*Vitis vinifera* L.). *Plant Soil*, **266**:129–142.

Phogat V., Skewes M.A., McCarthy M.G., Cox J.W., Šimůnek J., Petrie P.R., 2017. Evaluation of crop coefficients, water productivity, and water balance components for wine grapes irrigated at different deficit levels by a sub-surface drip. *Agric. Water Manag.*, **180**, 22–34.

Pou A., Gulías J., Moreno M., Tomás M., Medrano H., Cifre J., 2011. Cover cropping in *Vitis vinifera* L. *cv.* Manto Negro vineyards under Mediterranean conditions: Effects on plant vigour, yield and grape quality. *J. Int. des Sci. la Vigne du Vin*, **45**, 223–234.

Prada J., Dinis L.T., Soriato E., Vandelle E., Soletkin O., Uysal Ş., Dihazi A., Santos C., Santos J.A., 2024. Climate change impact on Mediterranean viticultural regions and site-specific climate risk-reduction strategies. *Springer Netherlands*, **29**, 52.

Puig-Sirera À., Rallo G., Paredes P., Paço T.A., Minacapilli M., Provenzano G., Pereira L.S., 2021. Transpiration and water use of an irrigated traditional olive grove with sap-flow observations and the FAO56 dual crop coefficient approach. *Water* (Switzerland), **13**, 2466.

Romero P., Botía P., Morote E., Navarro J.M., 2024. Optimizing deficit irrigation in Monastrell vines grafted on rootstocks of different vigour under semi-arid conditions. *Agric. Water Manag.*, **292**, 108669.

Romero P., García García J., Fernández-Fernández J.I., Muñoz R.G., Amor Saavedra F., Martínez-Cutillas A., 2016. Improving berry and wine quality attributes and vineyard economic efficiency by long-term deficit irrigation practices under semiarid conditions. *Sci. Hortic.*, **203**, 69–85.

Rosa R.D., Paredes P., Rodrigues G.C., Alves I., Fernando R.M., Pereira L.S., Allen R.G., 2012. Implementing the dual crop coefficient approach in interactive software. 1. Background and computational strategy. *Agric. Water Manag.*, **103**, 8–24.

Ruano-Rosa D., Sánchez-Hernández E., Baquero-Foz R., Martín-Ramos P., Martín-Gil J., Torres-Sánchez S., Casanova-Gascón J., 2022. Chitosan-Based Bioactive Formulations for the Control of Powdery Mildew in Viticulture. *Agronomy*, **12**, 495.

Santesteban L.G., Miranda C., Royo J.B., 2011. Suitability of pre-dawn and stem water potential as indicators of vineyard water status in *cv.* Tempranillo. *Aust. J. Grape Wine Res.*, **17**, 43–51.

Santesteban L.G., Miranda C., Marín D., Sesma B., Intrigliolo D.S., Mirás-Avalos J.M., Escalona J.M., Montoro A., Herralde F., Baeza P., et al. 2019. Discrimination ability of leaf and stem water potential at different times of the day through a meta-analysis in grapevine (*Vitis vinifera* L.). *Agric. Water Manag.*, **221**, 202–210.

Schultz H.R., 2016. Global Climate Change, Sustainability, and Some Challenges for Grape and Wine Production. *J. Wine Econ.*, **11**, 181–200.

Seljaninov G.T., 1966. Agroclimatic Map of the World. Hydrometeoizdat Publishing House, Leningrad.

Shellie K.C,. 2014. Water productivity, yield, and berry composition in sustained versus regulated deficit irrigation of merlot grapevines. *Am. J. Enol. Vitic.*, **65**, 197–205.

Silva J.N., Ponciano N.J., Souza C.L.M., Souza P.M., Viana L. H., Silva M.G.M., 2021a. Economic viability of 'Niágara Rosada' grape production in the north and northwest regions of Rio de Janeiro. *Ver. Bras. Frutic.*, **43,** e-672.

Silva S.P., Valín M.I., Mendes S., Araujo-Paredes C., Cancela J.J., 2021b. Dual crop coefficient approach in Vitis vinifera L. *cv.* Loureiro. *Agronomy*, **11**, 2062.

Silva S.P., Valín M.I., Mendes S., Araujo-Paredes C., Cancela J.J., 2024. Water productivity in *Vitis vinifera* L. *cv.* Alvarinho using dual crop coefficient approach. Agric. Water Manag. **303**, 109027.

Smith D.M., Scaife A.A., Eade R., Athanasiadis P., Bellucci A., Bethke I., Bilbao R., Borchert L.F., Caron L.P., Counillon F., 2020. North Atlantic climate far more predictable than models imply. *Nature*, **583**, 796–800.

Strack T., Stoll M., 2022. Soil water dynamics and drought stress response of *Vitis vinifera* L. in steep slope vineyard systems. *Agric. Water Manag.*, **274,** 107967.

Tonietto J., 1999. Les macroclimats viticoles mondiaux et l'influence du mésoclimat sur la typicité de la Syrah et du Muscat de Hambourg dans le sud de la France: méthodologie de caráctérisation. 233 p. PhD Thesis. Ecole Nationale Superieure Agronomique De Montpellier.

Trenti M., Lorenzi S., Bianchedi P.L., Grossi D., Failla O., Grando M.S., Emanuelli F., 2021. Candidate genes and SNPs associated with stomatal conductance under drought stress in Vitis. *BMC Plant Biol.*, **21,** 7.

Trigo-Córdoba E., Bouzas-Cid Y., Orriols-Fernández I., Mirás-Avalos J.M., 2015. Effects of deficit irrigation on the performance of grapevine (*Vitis vinifera* L.) *cv.* "Godello" and "Treixadura" in Ribeiro, NW Spain. *Agric. Water Manag.*, **161**, 20–30.

Tuccio L., Lo Piccolo E., Battelli R., Matteoli S., Massai R., Scalabrelli G., Remorini D., 2019. Physiological indicators to assess water status in potted grapevine (*Vitis vinifera* L.). *Sci. Hortic.* (Amsterdam), **255**, 8–13.

Vélez S., Rubio J.A., Andrés M.I., Barajas E., 2019. Agronomic classification between vineyards ('Verdejo') using NDVI and Sentinel-2 and evaluation of their wines. *Vitis J. Grapevine Res.*, **58,** 33–38.

Vilanova M., Rodríguez-Nogales J.M, Vila-Crespo J., Yuste J., 2019. Influence of water regime on yield components, must composition and wine volatile compounds of *Vitis vinifera cv.* Verdejo. *Aust. J. Grape Wine Res.*, **25**, 83–91.

Wagner M., Stanbury P., Dietrich T., Döring J., Ewert J., Foerster C., Freund M., Friedel M., Kammann C., Koch M., 2023. Developing a Sustainability Vision for the Global Wine Industry. *Sustain.*, **15**, 10487.

Williams L.E., Baeza P., 2007. Relationships among ambient temperature and vapor pressure deficit and leaf and stem water potentials of fully irrigated, field-grown grapevines. *Am. J. Enol. Vitic.*, **58,** 173–181.

Wilson T.G., Kustas W.P., Alfieri J.G., Anderson M.C., Gao F., Prueger J.H., McKee L.G., Alsina M.M., Sanchez L.A., Alstad K.P., 2020. Relationships between soil water content, evapotranspiration, and irrigation measurements in a California drip-irrigated Pinot noir vineyard. *Agric. Water Manag.*, **237**, 106186.

Winkler A.J., Cook J.A., Kliewer W.M., Lider L.A., 1974. General Viticulture. 710p. University of California Press, California.

WRB., 2014. World Reference Base for Soil Resources. World Soil Resources Reports, 106.

Zamorano D., Franck N., Pastenes C., Wallberg B., Garrido M., Silva H., 2021. Improved physiological performance in grapevine (*Vitis vinifera* L.) *cv.* Cabernet Sauvignon facing recurrent drought stress. *Aust. J. Grape Wine Res.*, **27**, 258–268.

Zia S., Spohrer K., Merkt N., Wenyong D., He X., Müller J., 2009. Non-invasive water status detection in grapevine (*Vitis vinifera* L.) by thermography. *Int. J. Agric. Biol. Eng.*, **2**:46–54.

Zufferey V., Verdenal T., Dienes A., Belcher S., Lorenzini F., Koestel C., Blackford M., Bourdin G., Gindro K., Spangenberg J.E., 2020. The influence of vine water regime on the leaf gas exchange, berry composition and wine quality of Arvine grapes in Switzerland. *OENO One*, **54**, 553–568.