horticulturae

Article

Monofilament Shading Nets Improved Water Use Efficiency on High-Temperature Days in Grapevines Subjected to Hyperarid Conditions

Gastón Gutiérrez-Gamboa [1,2], Emilio Villalobos-Soublett [3,4], Marco Garrido-Salinas [5,6] and Nicolás Verdugo-Vásquez [3,*]

[1] Instituto de Investigaciones Agropecuarias, INIA Carillanca, Temuco 4780000, Chile; gaston.gutierrez@inia.cl
[2] Escuela de Agronomía, Facultad de Ciencias, Ingeniería y Tecnología, Universidad Mayor, Temuco 4780000, Chile
[3] Instituto de Investigaciones Agropecuarias, INIA Intihuasi, La Serena 1722093, Chile; emilio.villalobos@inia.cl
[4] Programa de Doctorado en Ciencias Silvoagropecuarias y Veterinarias, Universidad de Chile, Santiago 8820808, Chile
[5] Centro de Estudios en Zonas Áridas (CEZA), Universidad de Chile, Coquimbo 1780000, Chile; marcogarrido@uchile.cl
[6] Departamento de Producción Agrícola, Facultad de Ciencias Agronómicas, Universidad de Chile, Santiago 8820808, Chile
* Correspondence: nicolas.verdugo@inia.cl; Tel.: +56-9-8391-2613

Abstract: (1) Background: Table grapes are often subjected to thermal stress during the growing season, affecting their production. Shading nets utilization has been proposed as an alternative to face this problem, but there is little available information about their effectiveness in hyperarid conditions. INIA-G2 vines were covered with kristall-colored mesh of 8% shade, and their ecophysiological responses were compared to uncovered vines during the daily cycle of two days with contrasting thermic conditions. (2) Methods: Net assimilation rate (A_N), stomatal conductance (g_s), transpiration (E), instantaneous water use efficiency (WUE: A_N E^{-1}), stem water potential (Ψ_s), air temperature (Ta) and vapor-pressure deficit (DPV) were determined in daily cycles (from 06:00 to 20:00 hrs) on two thermally contrasting days (330 DOY at 29.4 °C and 345 DOY at 22.6 °C) on grapevines without water restriction. (3) Results: The Ψ_s was not affected by treatment and day of measurement; nevertheless, A_N and g_s were statistically lower during 330 than 345 DOY (31% and 44% decrease, respectively). The covered vines presented less restrictive climatic conditions in terms of DPV in both DOY, reaching higher WUE values at 10, 12 and 14 h, which was associated with a decrease in E. (4) Conclusions: These results suggest that the use of shading nets can be an interesting alternative to cope with high temperatures in viticulture, improving the water use efficiency of vines. These are the first published results about the viticultural performance of the INIA-G2 variety.

Keywords: gas exchange; grapes; INIA-G2; protected viticulture; shading nets; *Vitis vinifera*; water status

Citation: Gutiérrez-Gamboa, G.; Villalobos-Soublett, E.; Garrido-Salinas, M.; Verdugo-Vásquez, N. Monofilament Shading Nets Improved Water Use Efficiency on High-Temperature Days in Grapevines Subjected to Hyperarid Conditions. *Horticulturae* **2024**, *10*, 176. https://doi.org/10.3390/horticulturae10020176

Academic Editors: Paolo Sabbatini and Gianluca Allegro

Received: 14 December 2023
Revised: 9 February 2024
Accepted: 12 February 2024
Published: 16 February 2024

1. Introduction

Chile holds a traditional history in the production of table grapes that originated in the early twentieth century in the Aconcagua Valley. Table grapes (*Vitis vinifera* L.) occupy a prominent place in the national fruit-growing surface area, covering an area of approximately 43,104 hectares, according to the national registers. The grapevines destined for table grapes are mostly distributed from the Atacama to O'Higgins regions since they offer optimal edaphoclimatic conditions for the development of this species [1,2]. However, in recent years, grape production has faced adverse environmental impacts, which are becoming increasingly common and notorious for producers [3]. In this context, extreme weather events such as rising global temperatures and changes in rainfall patterns have negatively affected the economic value of the national table grape industry [4,5]. Since

Chilean table grape production has a primarily export-oriented focus, the viticulturists have adapted to this situation using different sustainable solutions to protect their crops [6].

Plant growth and many developmental processes are strongly influenced by air temperature fluctuation, and each species has a functional temperature range, which is represented by minimum, optimum, and maximum values [7]. Heat stress increases temperature above the threshold level of plant optimum, and when it rises above the tolerance threshold, it may cause irreversible damage to plant tissues [3,7]. This physiological damage may disturb the normal cellular homeostasis, leading to retardation in growth and development and even death under extreme conditions [7,8]. Grapevines have internal adaptive mechanisms to face heat stress [9]. Metabolic processes such as respiration, photosynthesis and transpiration are very sensitive even in short-term temperature fluctuations [7]. Photosynthesis is the most critical process in plants that is directly or indirectly affected by temperature [3,7]. Heat stress considerably affects water status and gas exchange, reducing stomatal conductance, net CO_2 assimilation and water-use efficiency [7,10]. The optimum photosynthetic temperature for the grapevine is between 25 and 35 °C [11]. The transpiration rate increased substantially with the increase in leaf temperature above 35 °C, which is consistent with the need for enhanced evaporative cooling [12].

Protected viticulture is a concept that addresses different systems used to grow vines under controlled and protected environmental conditions. The use of protective structures such as shading, antihail, mosquito and photoselective nets are considered technologies from protected viticulture. These protection systems have gradually become an essential technology for table grape production and fruit growing in different climatic zones [6,13,14]. The use of these types of technologies is even more critical in geographical areas characterized by high solar radiation, extremely high temperatures and high vapor pressure deficits [6,15]. Shading nets have become an interesting alternative for grape production and are proposed as an adaptation technique to mitigate the impacts of global warming on viticulture due to their effects on decreasing temperatures and limiting evapotranspiration [16]. Shading nets covering the grapevines reduce the photosynthetic photon flux at the leaf surface available for photosynthesis, decreasing the temperature of the canopy and the fruit by up to 7 °C and incident radiation between 26% and 46%, depending on the selected net color [6,17]. Martínez-Lüscher et al. [18] reported that shade cloths covering the grapevine fruit zone may efficiently palliate temperature spikes, especially in the last weeks before harvest, while transmitting enough radiation into the grape zone compared to uncovered grapes.

Plant species close their stomata to reduce transpiration and maintain constant leaf water potential when the vapor pressure deficit is increasing [19]. Daytime transpiration is driven by evaporative demand and radiative energy [20]. As a consequence, leaf transpiration and sap flow values increased in the morning as solar radiation was intercepted and air temperature increased [21]. Nevertheless, a lapse was observed in the early hours of the morning between sap flow values, which remained very low despite light conditions and leaf transpiration on the external part of the canopy [21]. In this fashion, the measurements of gas exchange parameters during a daily cycle in grapevines subjected to different vapor-pressure deficits on two contrasted thermic days could provide useful information about the actions that can be taken on a warm day to mitigate its negative effects on grapevine productivity.

Based on the above mentioned, the aim of this study was to evaluate the ecophysiological responses of INIA-G2 vines covered with a kristall-colored mesh of 8% shade on two thermal contrasting days during the daily cycle and compare it to uncovered vines. To our knowledge, these results will be the first results provided to the scientific community about the viticultural performance of the INIA-G2 variety, and it is the first study to evaluate the effect of shading nets in table grape viticulture at a daily resolution scale.

2. Materials and Methods

2.1. Experimental Study and Treatments

The field experiment was conducted in an experimental INIA-G2 (*Vitis vinifera* L.) vineyard during the 2020–21 growing seasons, located at the "Biodiversity Research Center" belonging to the Instituto de Investigaciones Agropecuarias (INIA) (30°02 S, 70°41 W, 630 m above sea level; Coquimbo Region, Chile). The climate of the area is classified as hyperarid, with an average daily temperature of 16.1 °C and a mean annual rainfall of 100 mm that concentrates in winter (June–September). The reference evapotranspiration from September to March totaled 1047 mm. The vineyard soil is a sandy loam alluvial Entisol and has a flat topography (<1%). The soil holds moderate depth (>50 cm) with no physical restrictions for root growth. The vines of INIA-G2 (table grape cultivar) were grafted onto Harmony rootstock, planted during the 2018 winter at a planting distance of 1.75 m × 3.0 m, and trained on an overhead trellis system at a height of 2 m above the ground. The vines were managed according to the conventional viticultural practices used in the Elqui Valley in terms of leaf management, fertilization, growth regulator applications, irrigation, pruning and disease control. Due to the low rainfall that is recorded during the season and the high vapor pressure deficit, it is necessary to apply water through irrigation. In this regard, the vines were drip irrigated using one irrigation line per row with emitters supplying water at a rate of 2 L h^{-1} spaced at 0.5 m. The entire experimental site, approximately 1 hectare, was irrigated equally, supplying the crop demand through 3–4 irrigations per week.

Two treatments were randomly arranged in the vineyard in a completely randomized design, with four replicates as follows: (i) a control, in which vines were managed without a shading net (T0), and (ii) a kristall shading net that covered the vines with shade (T1). The shading net was composed of high-density polyethylene (HDPE) monofilament with an ultraviolet (UV) inhibitor that allowed 8% shade. The mesh size used was 3 × 7 mm, associated with the distance between warp and weft. The mesh weaving system was plain, and the hole shape was rectangular. The weight and diameter of the yarn were 45 g m^{2-1} and 0.30 mm, respectively. Each replicate was made up of 4 consecutive plants. The measurements were carried out in the central plant, leaving the other vines as a border among treatments. It is important to mention that the experimental vineyard belongs to the Table Grape Breeding Program of INIA-Biofrutales, where potential new varieties are evaluated. In this sense, there are more than 60 plants per variety for each condition (with mesh and without mesh) where the surface with mesh is 5000 square meters.

The shading nets were installed at a height of 4.0 m above the ground level parallel to the canopy, and they have been established since January 2019 permanently, considering the entire growth cycle of the vine. An automatic weather station (AWS) located 400 m from the vineyards was used to characterize the climatic conditions in terms of temperature, vapor pressure deficit and photosynthetically active radiation during the studied season. On the other hand, in each of the sectors, (with mesh and without mesh) temperature, relative humidity, wind speed and solar radiation sensors were established, with the aim of characterizing vine microclimate conditions throughout the growing season (Supplementary Figure S1).

2.2. Plant Measurements

During two contrasting days, different evaluations were carried out in 2-hour cycles, starting at 06:00 until 20:00. These days correspond to 330 DOY (phenological stage of "berries 10–12 mm") and 345 DOY (phenological stage of "berries 12–14 mm"). These days presented differentiated thermal behavior, as presented in the results. The 330 DOY was unusually warmer, while 345 DOY corresponds to normal thermal behavior for spring.

Physiological trait measurements included the stem water potential (Ψ_s) taken from fully mature and healthy leaves (two per replicate) located in the center of the west-facing vine canopy between 06:00 and 20:00 h for each day, using a pressure chamber (PMS Instrument Co., model 600, Corvallis, Oregon, USA). For these measurements, the leaves were covered with completely hermetic aluminum foil bags for at least 1 h before the measurement. Then, leaves were cut and immediately placed in the chamber.

Also, the stomatal conductance (g_s; mol H_2O m^2 s^{-1}), transpiration (E; mmol H_2O m^2 s^{-1}) and net assimilation rate (A_N; µmol CO_2 m^2 s^{-1}) were measured on full sun, developed, exposed to solar radiation and healthy mature leaves located in the middle third of the shoot (one leaf per replicate) facing west using a portable infrared gas analyzer (LI−6400 XT, LICOR Inc., Lincoln, NE, USA) equipped with a 6 cm^2 transparent leaf chamber. Three measurements were made in one leaf per replicate, so individual data consisted of the average of three determinations performed in the upper, middle and lower sides of each leaf. Environmental conditions in the leaf chamber were natural photosynthetically active radiation (PAR), a molar air-flow rate setting at 500 µmol s^{-1}, and a concentration of 400 µmol s^{-1} CO_2 that was kept constant by a CO_2 injector system provided by the manufacturer. Also, the intrinsic water use efficiency was calculated from the ratio between A_N and g_s (A_N g_s^{-1}; WUEi, µmol CO_2 mol H_2O^{-1}) and the instantaneous water use efficiency (WUE) from the ratio between A_N and E (A_N E^{-1}; WUE, µmol CO_2 mmol H_2O^{-1}). Additionally, leaf temperature, PAR radiation and vapor pressure deficit (VPD) were recorded using this equipment.

2.3. Statistical Analysis

The data were analyzed by means of an analysis of variance (ANOVA), considering different factors depending on the case (treatments, days of the year, the hour and interaction). A confidence level of 5% was considered, and the Tukey test was used in case of significant differences. The XLSTAT software, version 2020.3.1 (Addinsoft SARL, Paris, France), was used to perform all the analyses.

3. Results

3.1. Climatic Measured Variables

Figure 1 shows the daily measurements of maximum temperature (Max T), vapor pressure deficit (VPD) and photosynthetically active radiation (PAR) of the two thermally contrasting days studied (330 and 345 day of the year, as DOY). Similar PAR (µmol m^2 s^{-1}) conditions were observed in the 330 and 345 DOY, reaching maximum average values of 1744 and 1725 µmol m^2 s^{-1}, respectively, at 12:00 h (uncovered vines). Subsequently, at 13:00 h, 330 and 345 DOY reached an average PAR of 1700 and 1696 µmol m^2 s^{-1}, respectively, being the second hour of the day with the highest radiation in the day. Max T (°C) and VPD (kPa) showed wide differences between 330 and 345 DOY along the daily cycle. Max T ranged from 10.63 to 32.91 °C in the 330 DOY and reached the highest value at 13:00 h, whereas it varied from 11.33 to 27.31 °C in the 345 DOY and reached the highest value at 15:00 h. These highest values coincided with the maximum DPV values, which were reached at 13:00 and 15:00 h (3.88 and 2.21 kPa), respectively. The 330 DOY presented 7 h with temperatures higher than 30 °C, whereas 345 DOY did not show these temperatures. In addition, the average maximum temperature in the 330 and 345 DOY was 22.58 and 18.48 °C, respectively. The average VPD was 2.52 and 1.21 kPa in the 330 and 345 DOY throughout the day, respectively, whereas the daily sum of VPD from 06:00 to 20:00 h was 37.31 and 18.12 kPa in the 330 and 345 DOY, respectively. Based on this, 330 DOY presented showed a DPV 40% higher than 345 DOY between 12:00 and 16:00 h.

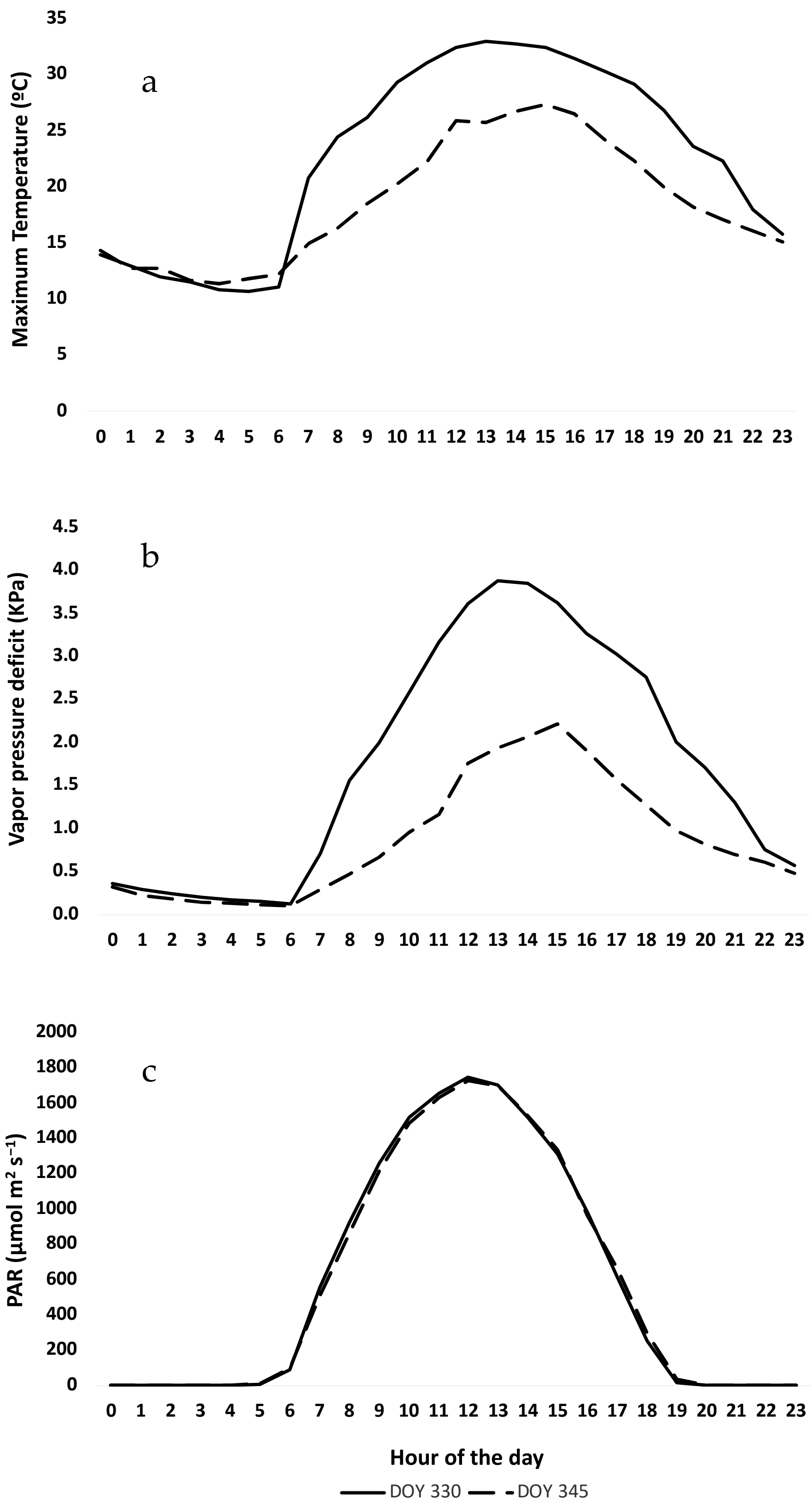

Figure 1. Hourly measurement of climatic variables for the day of the year (DOY) 330 and 345: (**a**) maximum temperature (°C); (**b**) vapor pressure deficit (VPD); (**c**) photosynthetically active radiation (PAR). Climatic data obtained from automatic weather station.

3.2. Effects of Shading Nets and Day of Measurement on Gas Exchange and Water Status of Vines

Table 1 shows the effects of shading nets and day-of-measurement factors on gas exchange and water status determinations of INIA-G2 grapevines. The day-of-measurement factor significantly influenced net CO_2 assimilation (A_N), stomatal conductance (g_s) and instantaneous water use efficiency (WUE), whereas treatments (shading nets) only affected transpiration (E). At similar vine water status in terms of the stem (Ψ_{Stem}) and leaf (Ψ_{Leaf}) water potential, the vines in the 345 DOY were subjected to higher A_N and g_s than the vines in the 330 DOY (45% and 79%, respectively), which significantly influenced its WUE (+ 53%). The vines' E was not affected by the day of measurement. Shading net treatments decreased E in vines compared to an unprotected system without affecting the rest of the gas exchange measurements and vine water status. The interaction of the factors did not affect the studied parameters.

Table 1. Effects of shading net treatments and day of measurement on gas exchange and water status of INIA-G2 vines.

	A_N (µmol CO_2 m^{-2} s^{-1})	g_s (mol H_2O m^{-2} s^{-1})	E (mmol m^{-2} s^{-1})	WUE_i (A_N g_s^{-1})	WUE (A_N E^{-1})	ψ_{Stem} (MPa)	ψ_{Leaf} (MPa)
			Day of the year (DOY)				
330 DOY	5.61 a	0.097 a	3.02 a	55.96 a	1.99 a	−0.37 a	−0.67 a
345 DOY	8.13 b	0.174 b	2.72 a	62.23 a	3.04 b	−0.39 a	−0.60 a
Significance	0.004	0.000	0.310	0.176	0.002	0.650	0.200
			Treatment (T)				
T0 Control	7.17 a	0.148 a	3.27 b	56.02 a	2.24 a	−0.38 a	−0.65 a
T1 Shading net	6.57 a	0.123 a	2.47 a	62.16 a	2.78 a	−0.38 a	−0.62 a
Significance	0.700	0.120	0.007	0.390	0.070	0.830	0.630
Interaction (DOY x T)	0.500	0.320	0.570	0.360	0.120	0.640	0.580

Significance (*p*-value) of day of the year (DOY), treatment (T) and DOY–T interactions. For a given factor and significance $p < 0.05$, different letters within a column represent significant differences (Tukey's test, $p < 0.05$). In red, *p*-value lower than 0.05. A_N: net CO_2 assimilation; g_s: stomatal conductance; E: transpiration; WUEi: intrinsic water use efficiency; WUE: instantaneous water use efficiency; Ψ_{stem}: stem water potential; $\Psi_{leaf:}$ leaf water potential.

3.3. Effects of Shading Nets on Each Day of Measurement on Gas Exchange and Water Status of Vines

Table 2 shows the effects of shading nets on each day of measurement on vine gas exchange and water status. Shading nets did not affect any of the gas exchange and water status parameters of the vines in the 330 DOY, whereas they affected E and WUE in the 345 DOY. The grapevines covered with shading nets in the 345 DOY presented lower E and higher WUE than the uncovered grapevines. The rest of the gas exchange and water status parameters measured in the vines were not affected by the utilization of the shading nets.

Table 2. Effects of shading net treatments for each day of measurement on gas exchange and water status of INIA-G2 vines.

	Treatment	A_N (µmol CO_2 m^{-2} s^{-1})	g_s (mol H_2O m^{-2} s^{-1})	E (mmol m^{-2} s^{-1})	WUE_i (A_N gs^{-1})	WUE (A_N E^{-1})	ψ_{Stem} (MPa)	ψ_{Leaf} (MPa)
330 DOY	T0 Control	6.00 a	0.10 a	3.37 a	56.70 a	2.02 a	−0.38 a	−0.70 a
	T1 Shading net	5.21 a	0.09 a	2.67 a	55.22 a	1.96 a	−0.36 a	−0.64 a
	Significance	0.52	0.36	0.17	0.88	0.77	0.63	0.51
345 DOY	T0 Control	8.33 a	0.19 a	3.18 b	55.35 a	2.47 a	−0.38 a	−0.60 a
	T1 Shading net	7.92 a	0.15 a	2.26 a	69.10 a	3.60 b	−0.39 a	−0.60 a
	Significance	0.570	0.190	0.004	0.140	0.016	0.860	0.950

For a given factor and significance $p < 0.05$, different letters within a column represent significant differences (Tukey's test, $p < 0.05$). In red, *p*-value lower than 0.05. A_N: net CO_2 assimilation; g_s: stomatal conductance; E: transpiration; WUEi: intrinsic water use efficiency; WUE: instantaneous water use efficiency; Ψ_{stem}: stem water potential; $\Psi_{leaf:}$ leaf water potential.

3.4. Daily Measurements of Ecophysiological Responses of Vines

Figure 2 shows leaf temperature (°C), leaf vapor pressure deficit (VPD) (kPa), and photosynthetically active radiation (PAR) in the vines measured at 330 (Figure 2a,c,d) and 345 (Figure 2b,d,f) DOY. The maximum temperature reached in the grapevines was 39.9 and 34.7 °C at 330 and 345 DOY, respectively. Leaf temperature was higher in uncovered grapevines at 08:00, 10:00, 12:00 and 14:00 h than in the grapevines covered by shading nets in the 330 DOY and at 08:00, 10:00 and 12:00 h in 345 DOY. Leaf VPD was higher in uncovered grapevines than in the grapevines covered at 09:00 and 10:00 h in 330 DOY and at 08:00, 10:00 and 12:00 h in 345 DOY. At 06:00 and 20:00 h, the grapevines covered with shading nets presented higher leaf temperature than the uncovered grapevines in 330 DOY and at 20:00 h in 345 DOY. At 06:00 h, the grapevines covered with shading nets presented higher leaf DPV than the uncovered grapevines in 330 DOY. The PAR level was higher in uncovered grapevines than the covered ones in each DOY, and it was similar in both studied DOYs. In most of the hours, grapevines measured on the 330 DOY showed higher leaf temperature and leaf VPD than the grapevines measured on the 345 DOY. Regarding the microclimatic conditions throughout the growing season under both situations (T0 and T1), the results are shown in Supplementary Figure S1. The highest differences are observed for variables such as wind speed and daily solar radiation. For temperatures, the differences are minimal, less than 0.6 °C, being higher in the condition without mesh.

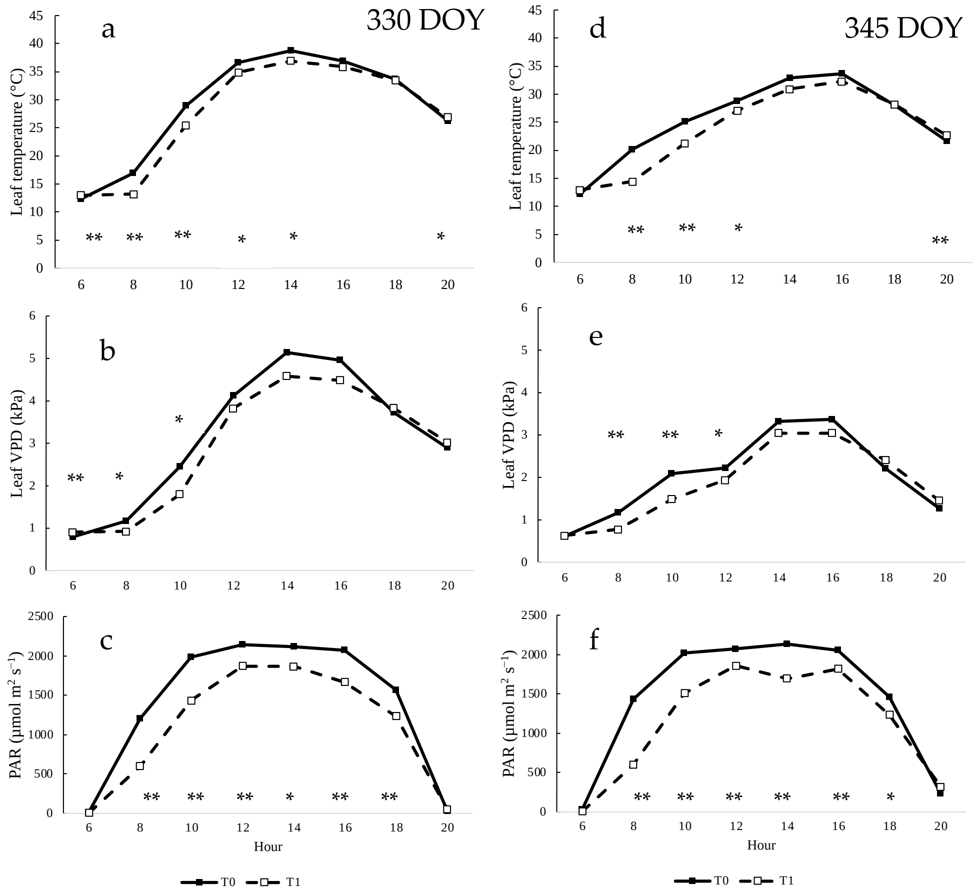

Figure 2. Daily measurement of ecophysiological variables determined in INIA-G2 grapevines for the day of the year (DOY) 330 (**a**–**c**) and 345 (**d**–**f**): (**a**,**d**) leaf temperature; (**b**,**e**) leaf vapor pressure deficit (VPD); (**c**,**f**) photosynthetically active radiation (PAR). T0: uncovered grapevines; T1: shading net treatment. ** Significant difference (p-value < 0.01). * Significant difference (p-value < 0.05).

3.5. Daily Measurements of Gas Exchange Parameters of Vines

Figure 3 shows net CO_2 assimilation (A_N), stomatal conductance (g_s) and transpiration (E) in vines measured at 330 and 345 DOY. The uncovered grapevines presented higher A_N at 08:00 h and E at 10:00 and 12:00 h than the covered grapevines in the 330 DOY. The covered grapevines presented lower A_N at 08:00 and 18:00 h and g_s at 12:00 and 18:00 h than the uncovered grapevines in the 345 DOY. A_N was higher in the covered grapevines than in the uncovered grapevines at 06:00 h in the 345 DOY. The uncovered grapevines presented higher E at 10:00 and 12:00 h and 08:00, 12:00, 14:00 and 18:00 h than in shaded grapevines in 330 and 345 DOY, respectively.

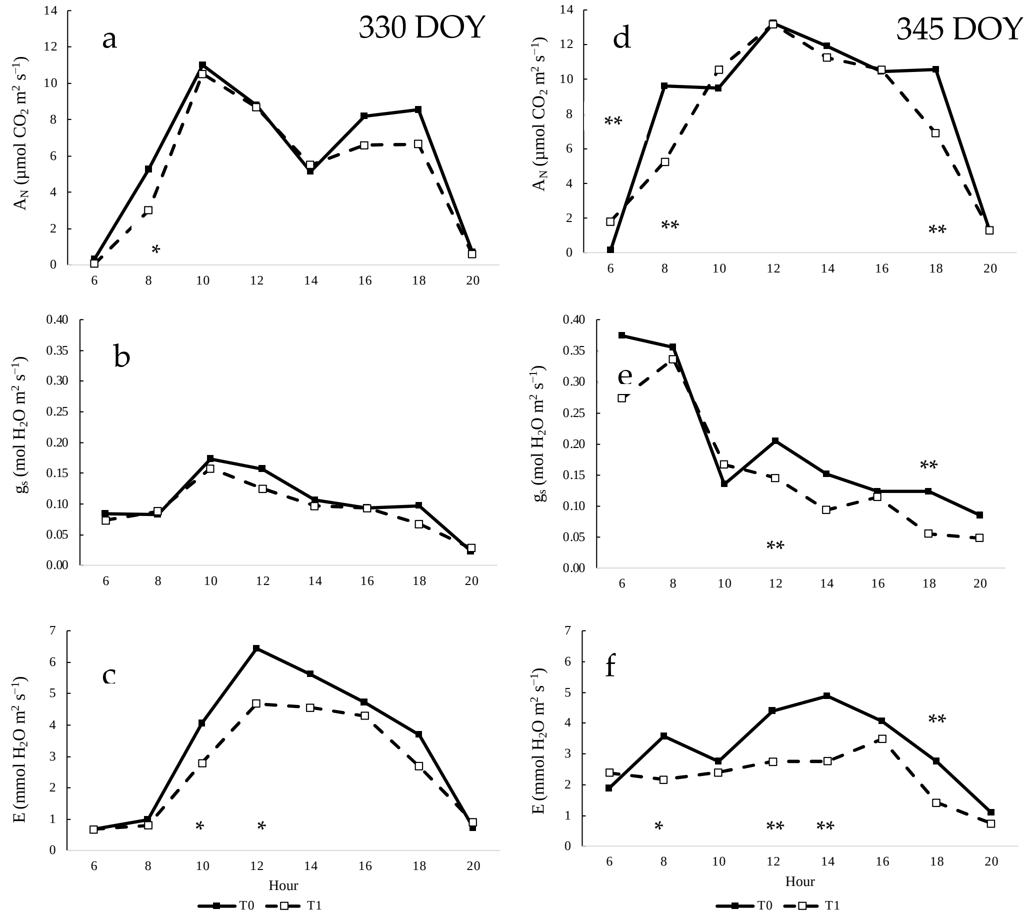

Figure 3. Daily measurement of gas exchange variables determined in INIA-G2 grapevines for the day of the year (DOY) 330 (**a**–**c**) and 345 (**d**–**f**): (**a**,**d**) net CO_2 assimilation; (**d**,**e**) stomatal conductance (g_s); (**c**,**f**) transpiration (E). T0: uncovered grapevines; T1: shading net treatment. ** Significant difference (p-value < 0.01). * Significant difference (p-value < 0.05).

3.6. Daily Measurements of Water Status Parameters of Vines

Figure 4 shows intrinsic water use efficiency (WUEi), instantaneous water use efficiency (WUE) and stem water potential (Ψ_s) in vines measured at 330 and 345 DOY. At 330 DOY, the uncovered grapevines presented lower WUE than the shaded grapevines at 10:00 and 12:00 h, as well as higher WUE than these same grapevines at 06:00 h, and WUEi was not affected by treatments. On this day, uncovered grapevines reached more negative (Ψ_s) than the shaded grapevines (at 08:00 h). At 345 DOY, uncovered grapevines presented lower WUE than the covered grapevines at 10:00, 12:00 and 14:00 h, as well as higher WUE than these same grapevines at 06:00 h. Uncovered grapevines presented lower WUEi than the shaded grapevines at 06:00 and 18:00 h, and Ψ_s was not affected by the treatments on the 345 DOY.

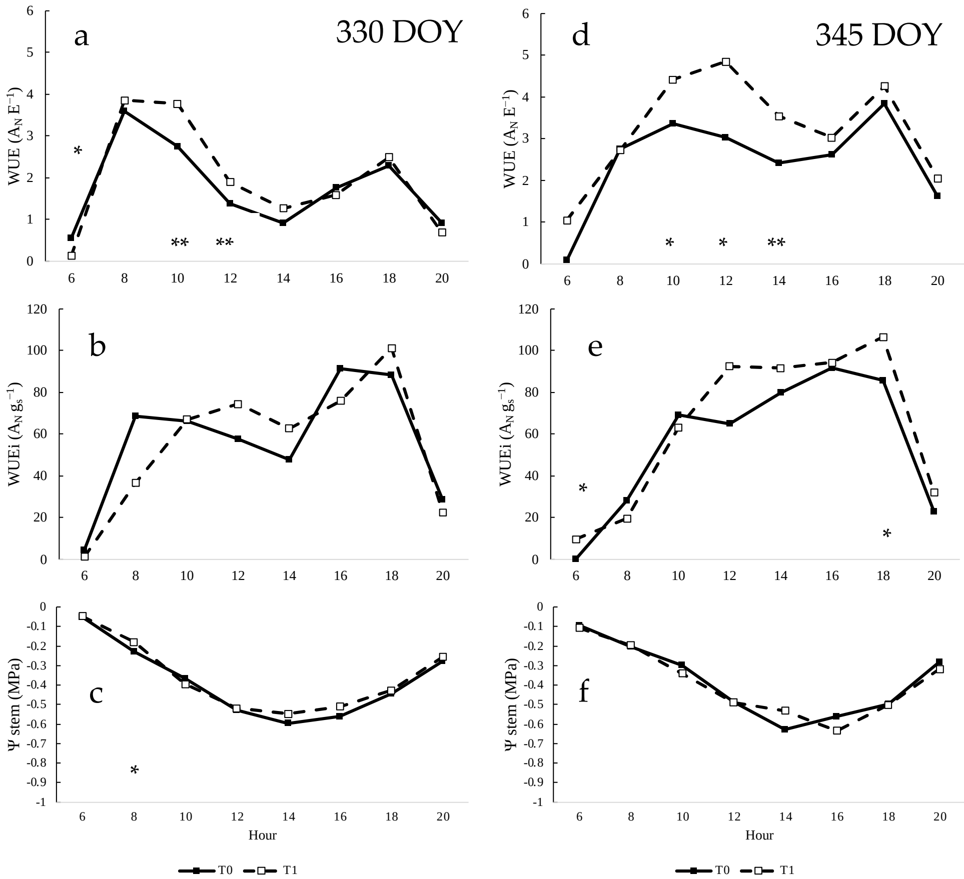

Figure 4. Daily measurement of water status variables determined in INIA-G2 grapevines for the day of the year (DOY) 330 (**a**–**c**) and 345 (**d**–**f**): (**a**,**d**) intrinsic water use efficiency (WUEi); (**d**,**e**) instantaneous water use efficiency (WUE); (**c**,**f**) stem water potential. T0: uncovered grapevines; T1: shading net treatment. ** Significant difference (*p*-value < 0.01). * Significant difference (*p*-value < 0.05).

4. Discussion

The high temperatures and vapor pressure deficit (VPD) reached on the warmest study day (330 DOY) considerably affected the photosynthesis (A_N) and stomatal conductance (g_s) of the vines compared to the ones measured on the coolest day (345 DOY), statistically decreasing their values despite that they were not stressed based on their stem water potential (Ψ_s: ~0.38 MPa). This resulted in a low carbon fixation capacity for the vine despite its low water requirements, decreasing its instantaneous water use efficiency (WUE) rather than its intrinsic water use efficiency (WUEi). Greer and Weston [22] showed that vines exposed to high temperatures during part of the growing season reduced their A_N close to 35%, while their transpiration (E) increased nearly threefold, which could be explained by a reduction in their g_s and an increase in the leaf VPD. In addition, it was reported that the average rate of A_N decreased with increasing temperature and was 60% inhibited at temperatures close to 45 °C compared to 25 °C [23]. In this study, A_N decreased by 31% for the reduction in g_s in 44%; the reduction in A_N exposed by the researchers was attributed to 15–30% stomatal closure [23]. The vine yield is closely related to net CO_2 assimilation throughout the season [3]. Data shown in the above sections are the result of the determinations performed on two individual days, and the accumulative effects of high temperatures during the season may considerably affect the vine yield. This aspect could be a line of research to be considered in the future based on the current climatic scenario. The results of yield and yield components for the season under study are shown in Supplementary Table S1. Slightly higher values are observed under the mesh condition (T1), although there are no significant differences. Similar results are observed for fruit maturity components (Total soluble solids and Titratable acidity (Supplementary Table S1).

Figure 3 shows a considerable decrease in A_N from 10:00 to 14:00 h compared to the trend observed in the g_s behavior. In this way, it is possible that under high temperatures, the nonstomatal limitations could be more related to A_N decrease in grapevines. These differences could be attributed to the specific climatic conditions of the locations selected for these studies. It is known that leaf temperature strongly modulates the PFD-dependent response of photosynthesis and PSII performance [24]. Light response curves at different temperatures revealed light-saturated photosynthesis to be optimal at 30 °C, but also PFDs saturating photosynthesis increased from 550 to 1200 µmol m^2 s^{-1} as temperature increased in a dry and semi-arid climate [23], below what is shown in this trial under dry and hyperarid conditions [25].

Currently, the improvement of water use efficiency in viticulture is a crucial subject for the table grape industry to improve vineyard sustainability, mostly in vineyards located in arid zones [26]. The studies are mostly focused on increasing the sustainability of water resources related to the use of viticultural technology and variety selection in terms of increasing soil water storage, reducing soil water loss and limiting transpiration losses [26–28]. Shading cover nets statistically decreased vine transpiration (E) on the coolest day of measurement (345 DOY), increasing its instantaneous WUE (Table 1). Shading nets limit the solar radiation incidence and could decrease vine water requirements and improve water use efficiency [6]. The instantaneous WUE can be expressed as the ratio of the rates of net CO_2 assimilation to water loss [29]. The leaf level of instantaneous WUE reflects the ratio of the rates of leaf net photosynthesis to transpiration. In this trial, shading nets improved instantaneous WUE on the coolest day due to their effects on reaching similar net CO_2 assimilation (in terms of µmol CO_2 m^{-2} s^{-1}) with reducing E (in terms of mmol m^{-2} s^{-1}) in the vines. Similar to this, Cartechini and Palliotti [30] reported that leaf transpiration rate was significantly reduced by shading nets in the early morning during flowering and in the early afternoon during veraison, whereas the calculated substomatal CO_2 concentration was not affected. Shading nets considerably decreased the photosynthetically active radiation (PAR) along the daily cycle of measurement, which has been widely exposed in different trials [3,6,31]. In addition, leaf temperature was decreased due to the use of shading nets in the most stressed hours throughout the day (Figure 2). Shading nets statistically decreased E in the hours before the solar zenith (at 10:00 and 12:00 h) on the warmest day, whereas they decreased it at most of the daily hours (at 8:00, 12:00, 14:00 and 18:00 h) on the coolest day. Recently, Pallotti et al. [32] suggested that the canopy microclimate modifications induced by shading nets may represent an interesting alternative to mitigate heat and water stress, improve water use efficiency and slow down ripening processes. These findings coincided with the exposed results in which shading nets increased the instantaneous WUE in most of the stressed hours in the daily cycle in both studied days due to their effects on the decrease in E. None of the rest of the gas exchange variables, such as A_N and g_s, were affected by the use of the shading nets on the warmest day.

Interestingly, shading nets increased temperature and VPD in the leaves at the beginning of the warmest day (at 06:00 h), resulting in a significant decrease in the instantaneous WUE (Figure 4). Moreover, shading nets increased leaf temperature at the end (at 20:00 h) of the warmest day (Figure 2). Night transpiration has been proven to be non-negligible and possibly considerably reduced under water stress, and under some conditions, it can account for 10% of daily transpiration losses [33–35]. Escalona et al. [35] reported that on very humid nights, these losses are nearly compensated by dew income, reducing the expected daily WUE of the whole plant [33]. In addition, Medrano et al. [33] reported that respiration losses represented around 33% of the total carbon gain for irrigated plants and close to 45% for water-stressed plants. These authors suggested a clear variation in respiration losses linked to vine water status and confirmed the respiratory losses' importance for understanding vine carbon balance, but also for the better understanding of dark respiration as the largest unknown factor related to leaf instantaneous and whole-plant WUE [33].

Despite the above-mentioned results, the WUE calculation in this trial was performed on the basis of instantaneous measurements of leaf photosynthesis and transpiration, assuming that they could be representative of the whole vine. In this sense, the comparison between instantaneous and the whole vine WUE values usually reveals a clear relationship [26], but it is not always the case [33], which could represent a limitation of this study. It is important to mention that under the conditions of this study, the vines were not subjected to water restriction. Therefore, future research should evaluate the combined effect of high temperatures and water deficit irrigation on the physiological behavior of grapevines under netting, including measurements of yield parameters and water use efficiency. According to the results exposed in this trial, shading nets could be an interesting strategy to mitigate heat stress in table grapes, improving vine water use efficiency, a crucial issue for viticulture in hyperarid zones.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/horticulturae10020176/s1, Figure S1: daily measurement of climatic variables for the growing season (October 2020–April 2021). (a) Maximum air temperature (°C); (b) minimum air temperature (°C); (c) maximum relative humidity (%); (d) minimum relative humidity (%); (e) wind speed (m s^{-1}); and (f) solar radiation (W $m^{2\ -1}$). Table S1: Yield and yield components for table grape cv INIA-G2, without mesh (T0) and under mesh (T1), 2020–21 season.

Author Contributions: Conceptualization, N.V.-V., G.G.-G. and E.V.-S.; methodology, N.V.-V. and E.V.-S.; software, E.V.-S. and G.G.-G.; validation, N.V.-V.; formal analysis, E.V.-S., G.G.-G. and N.V.-V.; investigation, N.V.-V., G.G.-G., E.V.-S. and M.G.-S.; data curation, E.V.-S. and N.V.-V.; writing—original draft preparation, E.V.-S., N.V.-V. and G.G.-G.; writing—review and editing, N.V.-V., G.G.-G., E.V.-S. and M.G.-S.; visualization, N.V.-V. and G.G.-G.; supervision, N.V.-V.; project administration, N.V.-V. All authors have read and agreed to the published version of this manuscript.

Funding: This work was supported by "Fundación para la Innovación Agraria" (FIA) through the PYT-2019-0083 project and support of Instituto de Investigaciones Agropecuarias (INIA).

Data Availability Statement: The data presented in this study are available on request from the corresponding and the first author.

Acknowledgments: The authors are grateful to Elizabeth Pastén and Marco Cabrera for their valuable technical support. E.V.-S. acknowledges the support provided by the National Agency for Research and Development (ANID)/Scholarship Program/DOCTORADO NACIONAL/2022–21231495.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zúñiga-Espinoza, C.; Aspillaga, C.; Ferreyra, R.; Selles, G. Response of Table Grape to Irrigation Water in the Aconcagua Valley, Chile. *Agronomy* **2015**, *5*, 405–417. [CrossRef]
2. Uquillas, C.; Torres, E.; Ibacache, A.; Defilippi, B.G. 'Iniagrape-One', a New Chilean Table Grape Cultivar. *HortScience* **2013**, *48*, 501–503. [CrossRef]
3. Gutiérrez-Gamboa, G.; Zheng, W.; Martínez de Toda, F. Current Viticultural Techniques to Mitigate the Effects of Global Warming on Grape and Wine Quality: A Comprehensive Review. *Food Res. Int.* **2021**, *139*, 109946. [CrossRef] [PubMed]
4. Verdugo-Vásquez, N.; Orrego, R.; Gutiérrez-Gamboa, G.; Reyes, M.; Zurita-Silva, A.; Balbontín, C.; Gaete, N.; Salazar-Parra, C. Climate Trends and Variability in the Chilean Viticultural Production Zones during 1985–2015. *OENO One* **2023**, *57*, 345–362. [CrossRef]
5. Stolpe, N.; Undurraga, P. Long Term Climatic Trends in Chile and Effects on Soil Moisture and Temperature Regimes. *Chil. J. Agric. Res.* **2016**, *76*, 487–496. [CrossRef]
6. Villalobos-Soublett, E.; Gutiérrez-Gamboa, G.; Balbontín, C.; Zurita-Silva, A.; Ibacache, A.; Verdugo-Vásquez, N. Effect of Shading Nets on Yield, Leaf Biomass and Petiole Nutrients of a Muscat of Alexandria Vineyard Growing under Hyper-Arid Conditions. *Horticulturae* **2021**, *7*, 445. [CrossRef]
7. Venios, X.; Korkas, E.; Nisiotou, A.; Banilas, G. Grapevine Responses to Heat Stress and Global Warming. *Plants* **2020**, *9*, 1754. [CrossRef]
8. Mathur, S.; Agrawal, D.; Jajoo, A. Photosynthesis: Response to High Temperature Stress. *J. Photochem. Photobiol. B* **2014**, *137*, 116–126. [CrossRef]
9. Ye, Q.; Yu, J.; Zhang, Z.; Hou, L.; Liu, X. VvBAP1, a Grape C2 Domain Protein, Plays a Positive Regulatory Role Under Heat Stress. *Front. Plant Sci.* **2020**, *11*, 544374. [CrossRef]

10. Gutiérrez-Gamboa, G.; Pérez-Donoso, A.G.; Pou-Mir, A.; Acevedo-Opazo, C.; Valdés-Gómez, H. Hydric Behaviour and Gas Exchange in Different Grapevine Varieties (*Vitis Vinifera* L.) from the Maule Valley (Chile). *South Afr. J. Enol. Vitic.* **2019**, *40*, 181–191. [CrossRef]
11. Zhang, K.; Chen, B.H.; Hao, Y.; Yang, R.; Wang, Y.A. Effects of Short-Term Heat Stress on PSII and Subsequent Recovery for Senescent Leaves of Vitis Vinifera L. Cv. Red Globe. *J. Integr. Agric.* **2018**, *17*, 2683–2693. [CrossRef]
12. Rogiers, S.Y.; Greer, D.H.; Hutton, R.J.; Landsberg, J.J. Does Night-Time Transpiration Contribute to Anisohydric Behaviour in a *Vitis Vinifera* Cultivar? *J. Exp. Bot.* **2009**, *60*, 3763. [CrossRef]
13. Blanco, V.; Zoffoli, J.P.; Ayala, M. High Tunnel Cultivation of Sweet Cherry (*Prunus Avium* L.): Physiological and Production Variables. *Sci. Hortic.* **2019**, *251*, 108–117. [CrossRef]
14. Guastella, D.; Sigwebela, M.; Suarez, E.; Stubbs, O.; Acevedo, J.; Engelbrecht, G. Effect of Photo-Selective Shade Nets on Pollination Process and Nut Development of *Corylus Avellana* L. *Front. Plant Sci.* **2020**, *11*, 602766. [CrossRef] [PubMed]
15. Gutiérrez-Gamboa, G.; Pszczólkowski, P.; Cañón, P.; Taquichiri, M.; Peñarrieta, J.M. UV-B Radiation as a Factor That Deserves Further Research in Bolivian Viticulture: A Review. *S. Afr. J. Enol. Vitic.* **2021**, *42*, 201–212. [CrossRef]
16. Naulleau, A.; Gary, C.; Prévot, L.; Hossard, L. Evaluating Strategies for Adaptation to Climate Change in Grapevine Production—A Systematic Review. *Front. Plant Sci.* **2021**, *11*, 607859. [CrossRef] [PubMed]
17. Lobos, G.A.; Acevedo-Opazo, C.; Guajardo-Moreno, A.; Valdés-Gómez, H.; Taylor, J.A.; Laurie, V.F. Effects of Kaolin-Based Particle Film and Fruit Zone Netting on Cabernet Sauvignon Grapevine Physiology and Fruit Quality. *OENO One* **2015**, *49*, 137–144. [CrossRef]
18. Martínez-Lüscher, J.; Chen, C.C.L.; Brillante, L.; Kurtural, S.K. Partial Solar Radiation Exclusion with Color Shade Nets Reduces the Degradation of Organic Acids and Flavonoids of Grape Berry (*Vitis Vinifera* L.). *J. Agric. Food Chem.* **2017**, *65*, 10693–10702. [CrossRef] [PubMed]
19. Gowdy, M.; Suter, B.; Pieri, P.; Marguerit, E.; Irvine, A.D.; Gambetta, G.A.; van Leeuwen, C. Variety-Specific Response of Bulk Stomatal Conductance of Grapevine Canopies to Changes in Net Radiation, Atmospheric Demand, and Drought Stress. *OENO One* **2022**, *56*, 205–222. [CrossRef]
20. Kukal, M.S.; Irmak, S. Nocturnal Transpiration in Field Crops: Implications for Temporal Aggregation and Diurnal Weighing of Vapor Pressure Deficit. *Agric. Water Manag.* **2022**, *266*, 107578. [CrossRef]
21. Zufferey, V.; Spring, J.L.; Verdenal, T.; Dienes, A.; Belcher, S.; Lorenzini, F.; Koestel, C.; Rösti, J.; Gindro, K.; Spangenberg, J.; et al. The Influence of Water Stress on Plant Hydraulics, Gas Exchange, Berry Composition and Quality of Pinot Noir Wines in Switzerland. *OENO One* **2017**, *51*, 37–57. [CrossRef]
22. Greer, D.H.; Weston, C. Heat Stress Affects Flowering, Berry Growth, Sugar Accumulation and Photosynthesis of Vitis Vinifera Cv. Semillon Grapevines Grown in a Controlled Environment. *Funct. Plant Biol.* **2010**, *37*, 206–214. [CrossRef]
23. Greer, D.H.; Weedon, M.M. Modelling Photosynthetic Responses to Temperature of Grapevine (*Vitis Vinifera* Cv. Semillon) Leaves on Vines Grown in a Hot Climate. *Plant Cell Environ.* **2012**, *35*, 1050–1064. [CrossRef] [PubMed]
24. Greer, D.H. Photon Flux Density and Temperature-Dependent Responses of Photosynthesis and Photosystem II Performance of Apple Leaves Grown in Field Conditions. *Funct. Plant Biol.* **2015**, *42*, 782–791. [CrossRef] [PubMed]
25. Verdugo-Vásquez, N.; Gutiérrez-Gamboa, G.; Díaz-Gálvez, I.; Ibacache, A.; Zurita-Silva, A. Modifications Induced by Rootstocks on Yield, Vigor and Nutritional Status on Vitis Vinifera Cv Syrah under Hyper-Arid Conditions in Northern Chile. *Agronomy* **2021**, *11*, 979. [CrossRef]
26. Flexas, J.; Galmés, J.; Gallé, A.; Gulías, J.; Pou, A.; Ribas-Carbo, M.; Tomàs, M.; Medrano, H. Improving Water Use Efficiency in Grapevines: Potential Physiological Targets for Biotechnological Improvement. *Aust. J. Grape Wine Res.* **2010**, *16*, 106–121. [CrossRef]
27. Hatfield, J.L.; Dold, C. Water-Use Efficiency: Advances and Challenges in a Changing Climate. *Front. Plant Sci.* **2019**, *10*, 429990. [CrossRef] [PubMed]
28. Medrano, H.; Tomás, M.; Martorell, S.; Escalona, J.M.; Pou, A.; Fuentes, S.; Flexas, J.; Bota, J. Improving Water Use Efficiency of Vineyards in Semi-Arid Regions. A Review. *Agron. Sustain. Dev.* **2015**, *35*, 499–517. [CrossRef]
29. Zhang, Y.; Yu, X.; Chen, L.; Jia, G. Whole-Plant Instantaneous and Short-Term Water-Use Efficiency in Response to Soil Water Content and CO_2 Concentration. *Plant Soil* **2019**, *444*, 281–298. [CrossRef]
30. Cartechini, A.; Palliotti, A. Effect of Shading on Vine Morphology and Productivity and Leaf Gas Exchange Characteristics in Grapevines in the Field. *Am. J. Enol. Vitic.* **1995**, *46*, 227–234. [CrossRef]
31. Agarie, S. Physiological Roles of Silicon in Photosynthesis and Dry Matter Production in Rice Plants I. Effects of Silicon and Shading Treatments. *Jpn. J. Crop Sci.* **1992**, *61*, 200–206. [CrossRef]
32. Pallotti, L.; Silvestroni, O.; Dottori, E.; Lattanzi, T.; Lanari, V. Effects of Shading Nets as a Form of Adaptation to Climate Change on Grapes Production: A Review. *OENO One* **2023**, *57*, 467–476. [CrossRef]
33. Medrano, H.; Tomás, M.; Martorell, S.; Flexas, J.; Hernández, E.; Rosselló, J.; Pou, A.; Escalona, J.M.; Bota, J. From Leaf to Whole-Plant Water Use Efficiency (WUE) in Complex Canopies: Limitations of Leaf WUE as a Selection Target. *Crop J.* **2015**, *3*, 220–228. [CrossRef]

34. Fuentes, S.; De Bei, R.; Collins, M.J.; Escalona, J.M.; Medrano, H.; Tyerman, S. Night-Time Responses to Water Supply in Grapevines (*Vitis Vinifera* L.) under Deficit Irrigation and Partial Root-Zone Drying. *Agric. Water Manag.* **2014**, *138*, 1–9. [CrossRef]
35. Escalona, J.M.; Fuentes, S.; Tomás, M.; Martorell, S.; Flexas, J.; Medrano, H. Responses of Leaf Night Transpiration to Drought Stress in *Vitis Vinifera* L. *Agric. Water Manag.* **2013**, *118*, 50–58. [CrossRef]