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Irrigation Protocols in Different Water Availability Scenarios for 'Crimson Seedless' Table Grapes under Mediterranean Semi-Arid Conditions

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Abstract: For three consecutive years (2015–2017), two deficit irrigation (DI) strategies were used in a 12-year old vineyard (cv. 'Crimson Seedless') to implement a sustainable irrigation protocol according to the available water for the farmer. Four different irrigation treatments were assessed: (i) Control (CTL), irrigated to satisfy the maximum crop water requirements throughout the entire growing season; two DI treatments irrigated as CTL except during post-veraison, when the vines were irrigated at 50% CTL: (ii) Regulated Deficit Irrigation (RDI); and (iii) Partial Root Drying (PRD), alternating the wet and dry sides of the root zone, and (iv) irrigated according to the criteria followed by the farmer (FARM), and conditioned by the availability of water each season. The DI strategies resulted in a 50% increase in water use efficiency in the first two years and 81% during the third year. Weekly deficit irrigation protocols are proposed, which specify a maximum difference of 0.22 MPa of midday stem water potential with respect to well-watered vines for a range of irrigation water availabilities between 4000 and 7000 m^3 ha^{-1}. An applied water prediction model based on the Gaussian regression using day of the year and maximum temperature of the day is also proposed.

Keywords: irrigators community; mediterranean climate; deficit irrigation (DI); plant water status; *Vitis vinifera*

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1. Introduction

Water scarcity has become a global problem, particularly in Mediterranean areas with high climatic demands and low rainfall, often less than 250 mm per year [1], where the negative effects of climate change could be accentuated. Consequently, water storage is a major environmental challenge which can limit the expansion of irrigated agriculture and economic development [1].

Limiting water availability may affect plant productivity [2–4]: moderate water deficit can reduce yield but will be beneficial for some aspects of fruit quality; severe water deficit reduces yield and fruit quality, and the absence of water exacerbates these negative aspects, thereby harming adequate crop production. At present, water scarcity also has negative consequences at large-scale irrigation communities, which may have many difficulties every year for obtaining the fresh water needed at the whole farm level during growing seasons. Therefore, in places where available water does not meet a crop's water requirements, farmers must distribute it appropriately throughout the growing cycle to maintain the sustainability of their farms.

To deal with the scarcity of water availability, water-saving agricultural countermeasures must be adopted [5]. One way to increase the efficient use of water for irrigation is to employ deficit irrigation (DI) strategies. The most common methods for applying DI strategies to optimize water resources are Regulated Deficit Irrigation (RDI) [6], and Partial Root Zone Drying (PRD) [7]. Both supply less irrigation during part(s) of the seasonal cycle of plant development, coinciding with periods of low sensitivity to water deficit.

Table grapes (*Vitis vinifera* L.) for the fresh fruit market are one of the most important crops in south-eastern Spain, where the Region of Murcia leads national production, with a cultivation area of 7,114 ha and a total production of 210,105 t [8], which represents more than 65% of total national production. Their production has been stimulated by the high quality of the product and the consumer's acceptance of the new seedless varieties such as 'Crimson Seedless' [9]. 'Crimson Seedless' is a red late table grape cultivar developed at the USDA-ARS in Fresno, California in the early 1990s. The berries are characterized by their excellent organoleptic properties, which include a crisp berry texture and sweet flavor [10]. Moreover, they have a great market acceptance due to their good resistance to cold storage [9] and exportable value [11]. However, 'Crimson Seedless' often fails to develop an adequate red color in Mediterranean areas [12], which has been linked with high temperatures during the maturation stage that inhibit the accumulation of anthocyanins, the pigments responsible for the red berry color [13,14].

Table grapes have been shown to be sensitive to the availability of water in the soil [15], considered to be one of the most important limiting factors in Mediterranean agricultural production [16]. Williams et al. [17] studied the yield response of 'Thompson Seedless' with a wide range of treatments, ranging from 20 to 140% of the crop evapotranspiration (ET_C). The results showed that values lower values of 4000 m^3 ha^{-1} and greater than 8000 m^3 ha^{-1} of water applied did not guarantee the best berry weight nor total yield. In addition, Vita Serman et al. [18] reported, in cv. 'Superior Seedless', a reduction in production in the irrigated treatment at 60% ET_C. However, in treatments in which more water was applied, above 70% ETc, they did not detect reductions in production. Faci et al. [10] obtained grape production just as well-irrigated vines in cv. Autumn irrigated at 60% in post-veraison, but highlighted a significant reduction in the cv. Crimson, with respect to the fully irrigated treatment. Therefore, as Permanhani et al. [19] pointed out, and considering the wide range of water requirements of the crop (2700–9500 m^3 ha^{-1} per season), the successful implementation of deficit irrigation in table grapes requires good knowledge of genotype behavior, environmental conditions, and the influence of the rootstock used.

Recent studies demonstrated that in 'Crimson Seedless', pre-veraison (before the change of berry color) is the most critical period for the application of RDI strategies, while during the post-veraison period, plant production is not affected by severe water deficit. Indeed, reductions in midday stem water potential (Ψ_s) of 0.2 MPa during the pre-veraison period promote reductions in berry growth, whereas reductions of 0.3 MPa post-veraison did not have any negative effect on yield or berry quality [9]. Conesa et al. [20] reported that post-veraison DI strategies in 'Crimson Seedless' enhanced berry coloration and the production of health-promoting bioactive compounds (i.e., resveratrol, antioxidant capacity). In addition, the authors, using an RDI strategy consisting of the application of 50% of ET_C, increased water use efficiency (WUE) by about 30% and obtained water savings of 35%. Pinillos et al. [14] showed that post-veraison irrigation reduction allowed earlier harvest, allowing growers to obtain commercial-grade clusters with water savings of 14.2% (RDI 50%) and 21.9% (RDI 25%), compared to the total amount applied to well-irrigated vines during post-veraison. Meanwhile, Faci et al. [10] did not observe significant differences in the yield and berry quality between RDI and control vines, with water savings of about 15% with RDI 60% of ET_C.

The main objective of this study was to implement deficit irrigation strategies in a commercial vineyard (cv. 'Crimson Seedless'), to provide farmers with an irrigation protocol that increases the sustainability of their farms by adapting the amount of irrigation water to the crop, according to water availability in the irrigation community.

2. Material and Methods

2.1. Study Area, Weather Conditions and Irrigation Treatments

The experiment was conducted over three consecutive years (2015–2017) at a commercial vineyard (*Vitis vinifera* L.) of 12-year-old 'Crimson Seedless' vines grafted onto Paulsen 1103 (3.5 × 3 m spacing) located in Molina de Segura (Murcia, SE Spain, 38°06′50.9″ N; 1°10′31.3″ W). The soil characteristics of the 0–60 cm layer was a silty clay loam texture, with a bulk density of 1.25 g cm^{-3}, organic matter content of 1.7%, and soil pH of 8. The volumetric soil water content in the 0–0.6 m soil layer was 0.32 m^3 m^{-3} and 0.17 m^3 m^{-3} at field capacity and wilting point, respectively.

The climate of the area is semiarid Mediterranean, with hot dry summers (maximum air temperature 38.7 °C) and mild winters (average temperature 8 °C). During the five years prior, average annual rainfall and reference evapotranspiration (ET_0) calculated according to the Penman-Monteith method [21], were 250 and 1310 mm, respectively. Temperature (T), relative humidity (RH), rainfall and other climatic parameters were recorded with an automatic weather station of the Servicio de Información Agraria de Murcia [22] located 8.5 km from the experimental plot. Crop evapotranspiration (ET_C) was determined weekly from the product of ET_0 and the crop coefficient (Kc) based on Williams et al. [1] and varying from 0.2 to 0.8 according to each phenological stage.

Four different irrigation treatments were assessed: (i) a control treatment (CTL) irrigated to satisfy maximum crop water requirements (ET_C-110%) through the entire growing season; (ii) a regulated deficit irrigation (RDI) treatment, irrigated as the CTL except during post-veraison, when the vines were irrigated at 50% of CTL; (iii) a partial root drying (PRD) treatment, irrigated as the RDI treatment (similar amount of water) but alternating the wet and dry sides of the root zone every 10–14 days, when 75% of the soil field capacity was reached in the dry root zone; and (iv) a farmer treatment (FARM), when irrigation was applied following the agronomic criteria of the commercial farm, according to the water availability in each growing season. In the CTL, RDI, and FARM treatments, the irrigation system was comprised of one drip-line per vine row with three self-compensating emitters (4 L h^{-1}) per vine, placed every 100 cm, whereas the PRD treatment used two drip-lines with three self-compensating emitters (4 L h^{-1}) per vine to each side of the root system. Irrigation was scheduled weekly with a frequency that varied from 1 to 2 times per day in spring-summer to 1–5 irrigations per week for the rest of the season.

The electrical conductivity (EC) of the irrigation water varied between 1.0 and 1.5 dS m^{-1}, according to the water source used from the Irrigation Community of 'Campotejar' [23]. Standard cultural practices (e.g., weed control, fertilization, pruning and girdling) were carried out by the technical department of the commercial orchard following the usual criteria of the area.

Irrigation was automatically controlled with a timer-irrigation programmer and electro-hydraulic valves. The amount of water applied for each irrigation treatment was measured with an in-line volumetric water meter. The experimental layout was a randomized complete block design with three block-replicates per irrigation treatment. Each replicate consisted of three adjacent rows of vines with seven vines per row. The five central vines of the central row were monitored, while the others served as border vines. A total of 252 vines were assessed in this experiment.

2.2. Measurements

Plant water status was estimated by measuring stem water potential at solar midday (Ψ_s) using a pressure chamber (Model 3000, Soil Moisture Equipment, Santa Barbara, CA, USA). Two shaded leaves were selected per replicate, and three replicates per irrigation treatment (n = 6) were obtained. The leaves were placed in plastic bags covered with aluminum foil for at least 2 h prior to the measurements, which were carried out every 7–14 days from May to October following the recommendations from Hsiao [24]. To estimate the intensity of stress endured by deficit irrigation treatments, the water stress integral (WSI) was calculated from the Ψ_s values, according to the equation defined by

Myers [25]. The accumulated water stress integral (WSI) for both RDI and PRD treatments was normalized with respect to the CTL treatment.

The dynamics of berry growth was obtained by changes in the berry's equatorial diameter using a digital caliper (Mitutoyo, CD-15D) on 90 tagged berries per treatment (30 berries per replicate). Total yield (from each harvestable pick) was determined in all the vines of the experiment at the time of commercial harvest. Water use efficiency (WUE) was determined as the ratio between yield and total irrigation applied. All the vines were pruned at the end of December of each year and the pruning fresh weight was determined annually in five vines per replicate (n = 15). The growing degree day (GDD) was calculated through the model obtained by Richardson et al. [26], by using a 10 °C base temperature [27,28].

The quality traits measured are described in Conesa et al. [9,20]. For determining the quality parameters of berry juice, 300 berries per replicate (900 berries per treatment) were used. The titratable acidity (TA) and total soluble solids (TSS) were also measured, and the results were expressed as g of tartaric acid per L for TA, and as °Brix for TSS. The maturity index (MI) was calculated as the ratio between TSS and TA.

All data were analyzed using one-way ANOVA procedures with SPSS (v. 9.1), and means were separated with Duncan's multiple range tests at $p < 0.05$.

2.3. Model Algorithm

To provide users with a useful and reliable irrigation treatment predictor, where the input variables are easy to obtain, a Gaussian Process Regression (GPR) algorithm was developed; see Rasmussen and Williams [29] for a detailed explanation of the method. GPR is a nonparametric, Bayesian approach to regression, working well on small datasets. In mathematical terms, it assumes that y is the dependent variable (for instance, irrigation treatment), and x is a matrix containing all explanatory variables (independent variables), so that y = f(x) + e, where f is an unknown function (linear or nonlinear), and e is an independent identically distributed Gaussian noise N $(0, \sigma^2)$. GPR assumes a Gaussian process prior, which can be specified using a mean function, m(x), and a covariance given by $K(x, x') + \sigma^2 \times I$, where K(x, x′) is a kernel matrix, I is the identity matrix, and x′ denotes the transpose of x. In this study, we have chosen a squared exponential kernel matrix whose entries are defined using Equation (1),

$$K(x_i, x_j) = \vartheta \exp\left(-\frac{(x_i - x_j)^2}{2h^2}\right) \tag{1}$$

where ϑ is a scaling factor and h modulates the interaction between each pair of components of the independent variables. Therefore, y follows a multivariate normal distribution $y \sim MN(m(x), K(x, x') + \sigma^2 \times I)$ whose model hyper-parameters are automatically optimized by maximizing the conditional log-likelihood of the distribution y | x. Finally, we compute the predictive posterior distribution on our points of interest which allows us to infer their expected values.

In this work, the dependent variables were CTL and RDI irrigation treatments, while the input data was reduced to day of the year (DOY) and maximum temperature of the day (Tmax) in order to simplify the model and make it accessible for a broad variety of users. Our training set comprised data gathered in 2015 and 2016, leaving the data obtained in 2017 for testing. The goodness-of-fit of the model was evaluated with the coefficient of determination (R^2). The GPR algorithm was implemented using MATLAB R2017.

3. Results

3.1. Agrometeorological Variables, Irrigation Water Applied and Plant Water Status

The seasonal evolution of the most relevant agrometeorological variables that occurred during the three experimental periods (2015–2017) is shown in Figure 1A–C. Mean annual values of ET_0 and vapor pressure deficit (VPD) were 5 mm × day^{-1} and 1.5 kPa, respectively; with minimum values of ET_0 (0.8 mm $\times$ day^{-1}) and VPD (0.15 kPa) reached in winter (December–January), and maximum values of ET_0 (7 mm $\times$ day^{-1}) and VPD (2.5 kPa), reached in summer (June), respectively. Total rainfall amounted to 260 and 204 mm for the years 2015 and 2017, respectively; whereas the season corresponding to year 2016 was the rainiest, registering a total of 450 mm that were concentrated in the months of March, September, and December.

Regarding the total irrigation water applied (Figure 1D–F), the FARM treatment was the most irrigated during the experiment, with an average of 6777 m^3 ha^{-1} during the first and third years and with a higher amount of water during the second year, which totaled 8650 m^3 ha^{-1}. Meanwhile, the CTL treatment received an average amount of water of 6520 m^3 ha^{-1}, similar to the FARM treatment in the first and third years, but much lower during the second year, which received 2138 m^3 ha^{-1} less water. Furthermore, the mean volumetric soil water content was almost constant in the top 0–60 cm of soil, with values close to that corresponding to field capacity ($\sim$ 0.328 m^3 m^{-3}) in the three years (data not shown). The two deficit irrigation treatments (RDI and PRD) received the same amount of water during the experiment, with a slightly higher amount in the first year (5039 m^3 ha^{-1}) than in the last two years (4203 and 4152 m^3 ha^{-1}, respectively), representing a 26% reduction with respect to the CTL during the first year and 34% in the last two years. Water reduction began at the beginning of the post-veraison period, which occurred approximately in mid-July and coincided with a period without rain and the highest climatic demand of the year (Figure 1A).

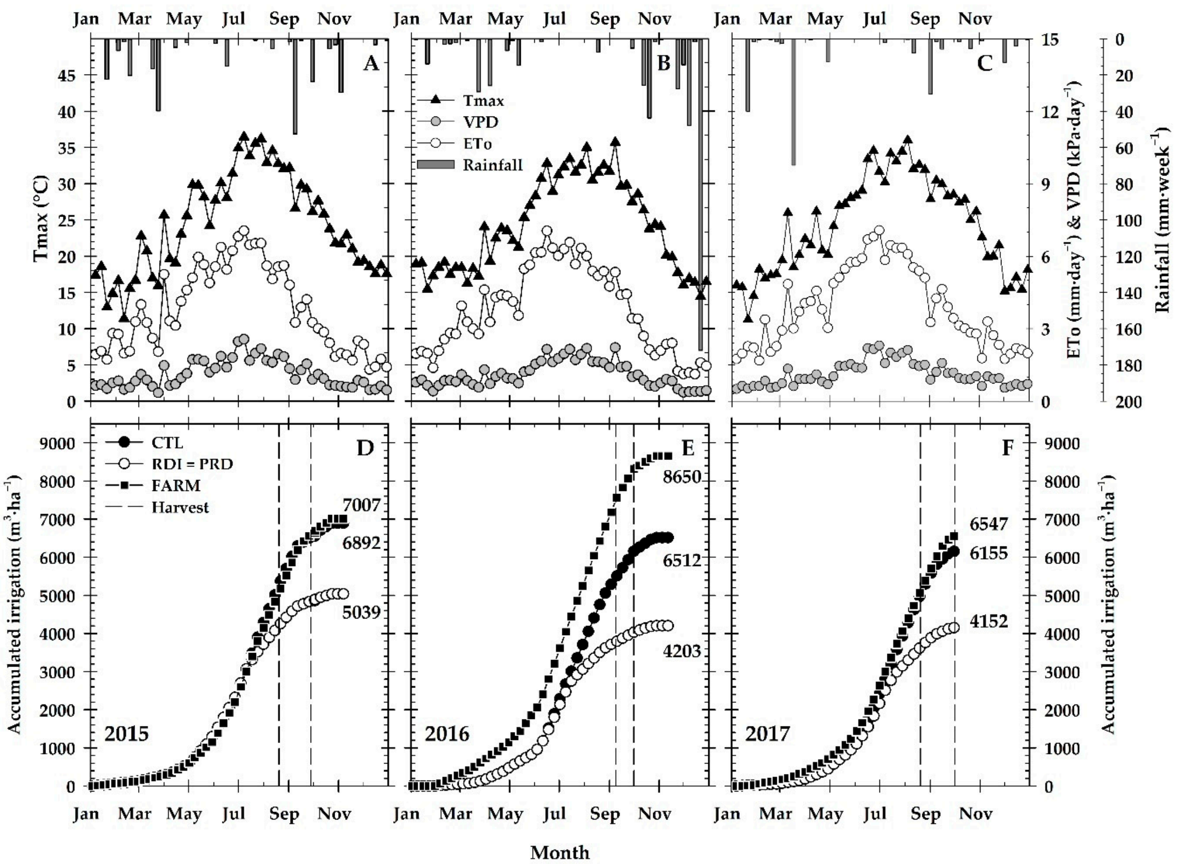

Figure 1. Seasonal evolution of daily reference crop evapotranspiration (ET_0), vapor pressure deficit (VPD), maximum temperature (Tmax) and weekly rainfall during the three years assayed (2015–2017) (**A**–**C**). Precipitation events are shown as vertical bars. Seasonal variation of cumulative water applied during the same experimental period (**D**–**F**). The total amount of water applied in all the treatments is also indicated. Vertical dashed lines indicate harvest periods.

Figure 2A–C shows the distribution of the irrigation applied during the experimental period, distinguishing the water accumulated during pre- and post-veraison phenological stages. In the first period—considered to be a critical period—during which an average of 1480 °C GDD was accumulated, the water applied was similar in the CTL and the two DI treatments, ranging from 3000 m^3 ha^{-1}, for the first year, to 2700 m^3 ha^{-1} for the last two. While during the second period—considered to be a non-critical period—it was observed that the CTL treatment received a similar amount of water in all three years, around 3800 m^3 ha^{-1}, whereas the two DI treatments received 48 and 53% of the control, in the first and last two years, respectively.

Figure 2D–F shows the weekly irrigation scheduling applied to each irrigation treatment. From the start, the amount of water applied increased exponentially each week, depending on the climatic demand, from values of around 8 m^3 ha^{-1} week, up to around 420 m^3 ha^{-1} week as the average maximum value reached in July, just before the start of veraison. Afterwards, while the control treatment was irrigated with around 360 m^3 ha^{-1} per week during the summer months, the vines with deficit irrigation reached around 180 m^3 ha^{-1}, decreasing to 30 m^3 ha^{-1} from August to the end of October, when the irrigation was suppressed (Figure 2D–F).

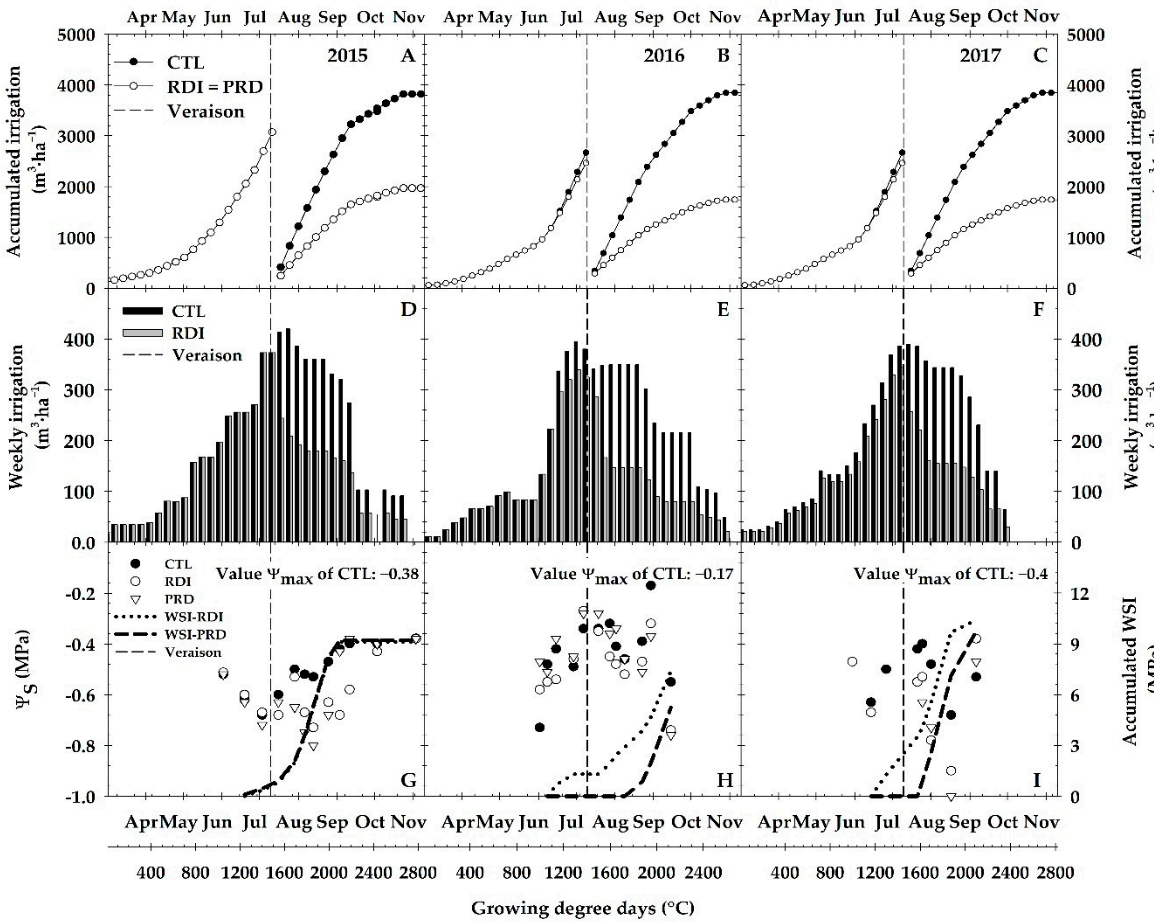

Figure 2. Seasonal cumulative water applied (**A**–**C**), irrigation water applied weekly (**D**–**F**); and stem water potential (**G**–**I**) and cumulative water stress integral (**G**–**I**) for all irrigation treatments: CTL (black circles), RDI (white circles) and PRD (white inverted triangles) during the three years assayed (2015–2017). The vertical dash line indicates the start of the post-veraison period.

The accumulated water stress integral (WSI), obtained from the midday stem water potential values, increased in the deficit irrigation treatments as the post-veraison period advanced, reaching values of 9, 7, and 10 MPa day, for the RDI treatment in 2015, 2016, and 2017, respectively (Figure 2G–I). The values achieved by the PRD treatment were slightly lower than the RDI during the second and third year, by 29% and 6.5%, respectively. The values of stem water potential at midday (Ψ_s) were dependent on the water demand (Figure 1A–C and Figure 3A–C) and the irrigation applied (Figure 2), reaching the highest values at the end of May and at the end of the growing season (end of September), and the lowest values coinciding with the summer months. The CTL and DI vines averaged −0.53 MPa in the pre-veraison period, with minimum values of around −0.7 MPa during the first and third year at the end of the pre-veraison period, and during the second year for the short-term irrigation applied, in the case of the CTL treatment (Figure 2E). During the post-veraison period, the CTL treatment averaged values of around −0.44 MPa. The DI treatments showed a reduction of around 0.22 and 0.27 MPa, for RDI and PRD treatments, for the first and third year, respectively, being slightly lower in the second year by around 0.19 MPa (Figure 2G–I). The differences between the treatments remained for about 2 months from the start of the water deficit period, being more constant in the RDI treatment, although the PRD vines had more negative Ψ_s values during the first and third years. The rainfall in September recovered these values to CTL levels (Figure 2G–I). The values corresponding to the FARM treatment showed important one-time differences with respect to the CTL treatment in both pre-veraison and post-veraison periods, oscillating between 0.1 and 0.3 MPa, respectively (Figure 3).

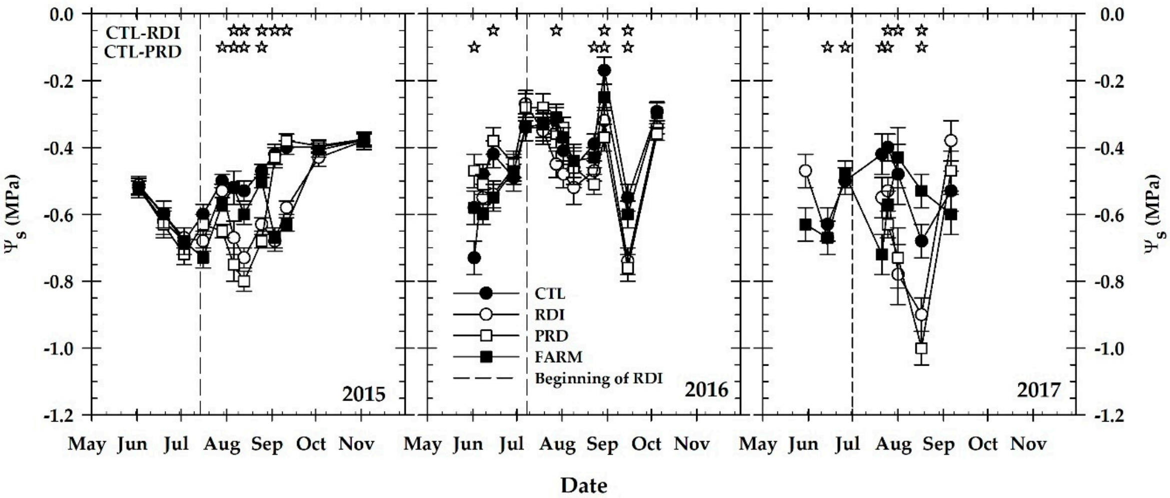

Figure 3. Seasonal evolution of midday stem water potential (Ψ_s, MPa) for all irrigation treatments: CTL (black circles), RDI (white circles), PRD (white squares) and FARM (black squares) during the three years assayed (2015–2017). Each point is the mean ± SE of n = 6 leaves, per irrigation treatment. The dashed line indicates the start of water deficit period. Stars indicate statistically significant differences between treatments according to Duncan's multiple range test ($p < 0.05$).

3.2. *Reproductive and Vegetative Patterns*

The dynamics of berry growth, from the equatorial diameter values measured, are shown in Figure 4. The berries experienced an exponential growth until the middle of July, slowing down afterwards, and reaching the maximum growth at the end of August.

The DI treatments did not reduce the berry size in any of the three years studied, mainly due to the fact that in the post-veraison period, when the irrigation water was reduced, the size of the berry suffered a strong decrease in its equatorial growth (Figure 4). Although coinciding with a water stress of around 0.15 and 0.32 MPa in the second and the third year, respectively (Figure 3), the equatorial diameter in the RDI treatment was occasionally significantly smaller than the CTL treatment. However, the final berry size at harvest was similar in the RDI treatment with respect to the CTL treatment (Table 1). On the other hand, the fruit size in the RDI treatment shown in 2016, just before the application of water deficit, was slightly greater than the rest of the treatments, coinciding with higher values of Ψ_s (Figures 3 and 4).

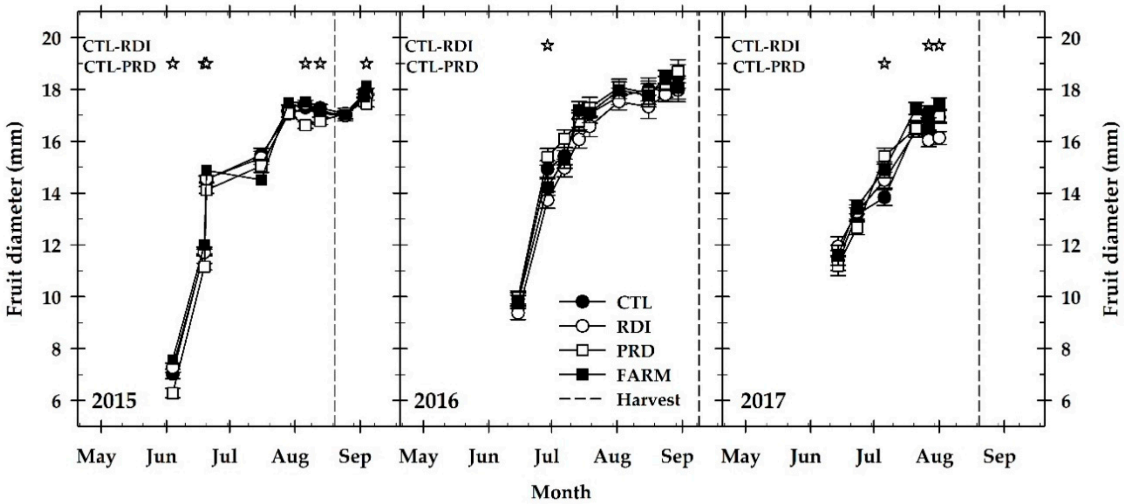

Figure 4. Evolution of the fruit equatorial diameter for all irrigation treatments: CTL (black circles), RDI (white circles), PRD (white squares) and FARM (black squares) during the three years assayed (2015–2017). Each point is the mean ± SE of $n = 60$ fruit. Vertical dashed lines indicate veraison for every season. Stars indicate statistically significant differences between treatments according to Duncan's multiple range test ($p < 0.05$).

Pruning weight obtained during vine dormancy (December) is shown in Figure 5. In general, the fresh weight of the pruning for all the treatments showed an upward trend as the trial progressed and according to the crop's development, with mean values ranging from 4.8 to 7 kg vine^{-1} for the first and third year, respectively. However, the weight was not altered by the water deficit applied, due to the variability of the measurements obtained (Figure 5).

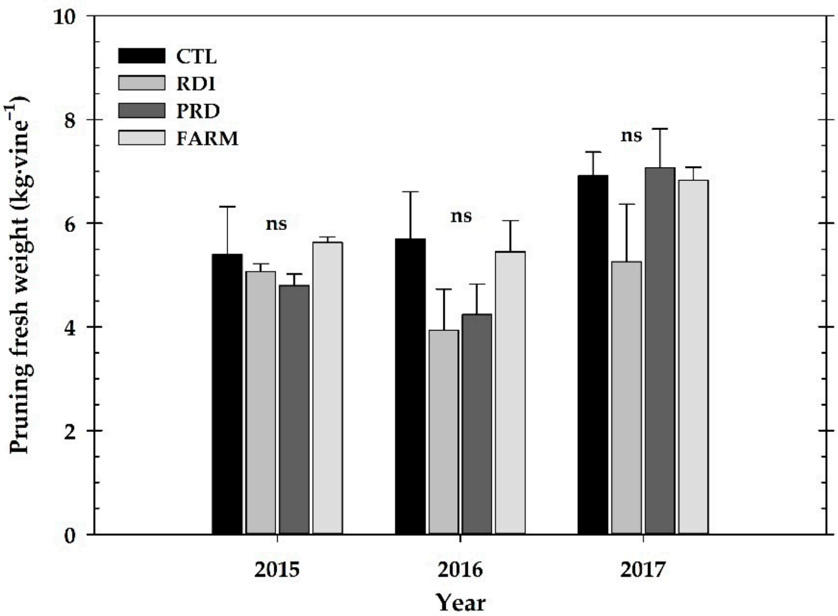

Figure 5. Mean values of pruning fresh weight for all irrigation treatments during the experimental period (2015, 2016 and 2017). Vertical bars indicate the standard error ($n = 18$). Columns with different letters denote significant differences according to Duncan's multiple range test ($p < 0.05$).

No significant differences in the total yield were found among irrigation treatments (Table 1). Indeed, the highest yields were observed in 2016 as shown by a significantly greater number of berries per cluster and a higher berry weight. The number of clusters was not affected by the irrigation treatments either (Table 1). The number of berries per cluster, and the individual berry/cluster mean weights were significantly affected by the irrigation treatments. The greater the number of berries found; the more berries/clusters obtained. Indeed, the treatment x season interaction (T × S) only showed significant differences in these parameters. Thus, yield parameters were affected to a larger extent by the season considered (S) than the irrigation treatment effect (T). Finally, comparing PRD and RDI, no significant difference in total yield or its components were found (Table 1).

Table 1. Mean values of total yield per vine, number of clusters, mean weight of clusters, number of berries and mean weight of berries evaluated at harvest during the three years assayed (2015–2017), for all the irrigation treatments: Control, RDI, PRD and FARM. Values are means ± SE (*n* = 15 vines per treatment).

Year /Treatment	Total Yield (kg·Vine^{-1})	Number of Clusters (Clusters·Vine^{-1})	Number of Berries (Berries·Clusters^{-1})	Mean Weight of Clusters (g)	Mean Weight of Berries (g)
2015					
CTL	19.76 ± 5.28 a	57.4 ± 13.6 a	66.51 ± 4.94 ab	344.25 ± 19.58 ab	5.09 ± 0.11 a
RDI	21.63 ± 7.41 a	58.6 ± 24.6 a	82.61 ± 4.41 c	369.11 ± 29.29 b	4.73 ± 0.22 a
PRD	13.7 ± 1.51 a	49.0 ± 6.5 a	60.07 ± 4.07 ab	279.59 ± 14.17 a	4.71 ± 0.09 a
FARM	25.29 ± 7.49 a	67.6 ± 18.4 a	77.14 ± 3.37 bc	374.11 ± 16.73 b	4.81 ± 0.04 a
2016					
CTL	32.2 ± 2.4 a	41.5 ± 2.1 a	148.55 ± 7.91 b	775.90 ± 41.6 b	5.25 ± 0.19 a
RDI	31.5 ± 2.5 a	53.5 ± 6.0 a	108.79 ± 4.65 a	588.79 ± 25.2 a	5.43 ± 0.29 a
PRD	32.7 ± 2.4 a	56.3 ± 6.0 a	95.69 ± 3.991 a	580.81 ± 23.7 a	6.07 ± 0.28 a
FARM	33.1 ± 2.4 a	57.4 ± 5.5 a	105.35 ± 1.53 a	576.66 ± 8.35 a	5.48 ± 0.46 a
2017					
CTL	16.6 ± 2.68 a	37.4 ± 5.9 a	106.92 ± 6.03 a	443.85 ± 38.76 a	4.21 ± 0.14 a
RDI	20.31 ± 7.2 a	50.8 ± 18.9 a	100.45 ± 7.29 a	399.80 ± 24.55 a	4.16 ± 0.15 a
PRD	22.75 ± 4.02 a	55.7 ± 9.7 a	91.78 ± 5.32 a	408.44 ± 7.51 a	4.49 ± 0.33 a
FARM	18.61 ± 1.41 a	43.3 ± 2.8 a	114.88 ± 10.06 a	429.79 ± 19.23 a	3.87 ± 0.30 a
Treatment (T)	ns	ns	***	***	ns
Year (y)	***	ns	***	***	***
T × y	ns	ns	***	***	***

Means within columns for a given year, followed by a different letter were significantly different according to Duncan multiple range test ($p < 0.05$). *** denotes significance at $p < 0.001$ and ns = not significant.

Figure 6 shows the number of grapes obtained in the different harvest events of years 2015 and 2016, which is indicative of the precocity of each irrigation treatment. Compared to the CTL treatment, the RDI treatment obtained similar values in both years assessed, whereas PRD was lower in 2016. Compared to the FARM treatment, the RDI treatment significantly increased the crop yield in both years, whereas PRD obtained similar values.

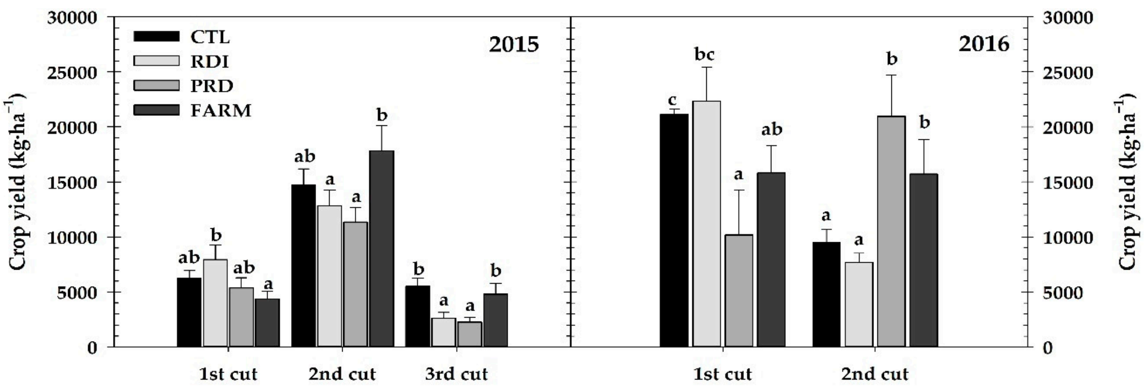

Figure 6. Crop yield (kg·ha^{-1}) evaluated at each harvest during the harvest period (from September to November) in all irrigation treatments (Control, RDI, PRD, and Farm) during the first two years (2015 and 2016). Bars are the means ± SE (n = 3). Vertical bars indicate the standard error. Columns with different letters denote significant differences according to Duncan's multiple range test ($p < 0.05$).

3.3. Berry Quality Patterns

No significant differences were observed in the chemical quality traits (total soluble solids (TSS), total acidity (TA), and maturity index (MI)) during the first and second years assayed. Interestingly, in the third year, berries from the RDI treatment showed the lowest levels of TA and thus an increase in the mean MI values (Table 2).

Table 2. Mean values for the chemical parameters (TSS, total soluble solids; TA, titratable acidity, MI, maturity index) evaluated at harvest during the three years assayed (2015–2017), for all the irrigation treatments: Control, RDI, PRD and FARM. Values are means ± SE (n = 9 vines per treatment).

Year/Treatment	Total Soluble Solids (°Brix)	Titratable Acidity (g L^{-1})	Maturity Index (MI)
2015			
CTL	17.6 ± 0.2 a	4.5 ± 0.2 a	40.0 ± 1.7 a
RDI	17.8 ± 0.2 a	4.2 ± 0.1 a	43.6 ± 1.4 a
PRD	17.8 ± 0.2 a	4.4 ± 0.2 a	41.7 ± 1.8 a
FARM	17.7 ± 0.2 a	4.5 ± 0.2 a	40.6 ± 1.7 a
2016			
CTL	17.5 ± 0.3 a	3.5 ± 0.2 a	50.2 ± 3.0 a
RDI	17.5 ± 0.5 a	3.4 ± 0.0 a	51.8 ± 2.3 a
PRD	17.1 ± 0.3 a	3.6 ± 0.2 a	47.6 ± 1.6 a
FARM	17.3 ± 0.4 a	3.6 ± 0.1 a	48.1 ± 0.2 a
2017			
CTL	18.8 ± 0.3 a	3.3 ± 0.3 ab	57.5 ± 3.8 ab
RDI	19.2 ± 0.4 a	2.9 ± 0.1 a	66.4 ± 3.6 b
PRD	18.9 ± 0.1 a	3.1 ± 0.0 ab	60.3 ± 0.7 ab
FARM	19.0 ± 0.3 a	3.5 ± 0.1 b	54.4 ± 2.7 a
Treatment (T)	ns	*	***
Year (y)	***	***	***
T × y	ns	ns	ns

Means within columns for a given year, followed by a different letter were significantly different according to Duncan multiple range test ($p < 0.05$). * and *** denotes significance at p = 0.05 and 0.001, respectively; ns = not significant.

3.4. Predictive Model

A Gaussian Process Regression model was implemented to estimate the amount of water applied in the CTL and RDI treatments as compared to the amount observed in 2017 using day of the year (DOY) and maximum temperature (Tmax) of the day as the explanatory variables. The data was split into training and testing sets. The training set comprised data from 2015 and 2016, when the GPR was estimated. This estimated model was used to forecast the CTL and RDI in the testing set comprised by data from year 2017. Figure 7 illustrates the observed and estimated CTL and RDI together with an error bar of plus/minus one standard deviation. The coefficient of determination was 0.995 for CTL and 0.978 for RDI, showing a strong and positive correlation and a high goodness-of-fit in both cases.

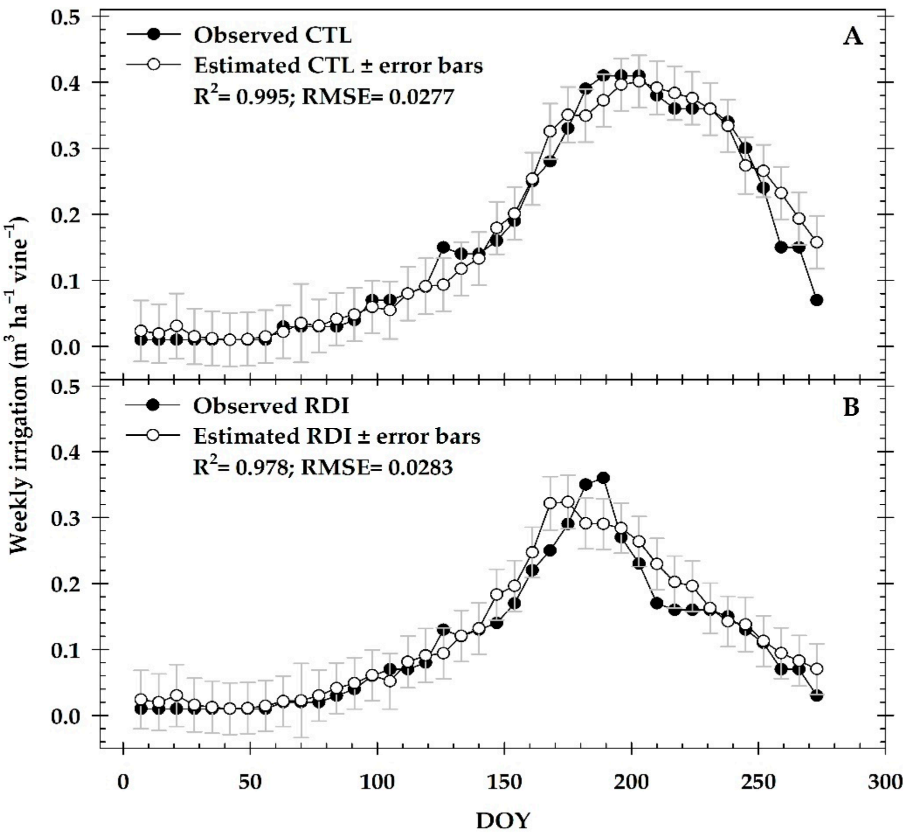

Figure 7. Estimated (white circles) and observed (black circles) weekly irrigation ($m^3 \cdot ha^{-1} \cdot vine^{-1}$) for CTL (**A**) and RDI (**B**) treatments referenced to the day of the year (DOY) for 2017.

4. Discussion

The phenological stage following veraison (post-veraison) can be considered a non-critical period when planning deficit irrigation strategies for table grape cv. 'Crimson seedless'. In our trial, an average weekly water supply of 160 m^3 ha^{-1} was applied to the vines during the summer (from mid-July to the end of September). This reduction represents savings of more than 50% with respect to well-irrigated vines during this period, and 30% over the entire crop cycle -averaging 2054 m^3 ha^{-1} during the entire experimental period. This behavior differs from grapevines, with pre-veraison considered to be a non-critical period, because table grapes need more water, as they require a greater leaf area to supply photoassimilates to developing berries, allowing for large berries for fresh consumption [30,31].

The DI strategies promoted a 50% increase in water use efficiency (WUE) in the first two years and an 81% increase during the third year, being only significant in the second year, reaching a value of 7.14 kg m^{-3} for the RDI treatment, while the control treatment averaged 3.34 kg m^{-3} during the experimental period. The values reached by the PRD treatment were slightly higher than the RDI during the last two years, but without significant differences observed (data not shown, and obtained from Figure 1 and Table 1). Permanhani et al. [19] reviewed the response of table grapes to deficit irrigation from different researchers, obtaining a wide range of WUE values for different cultivars, with the highest values obtained when the water deficit was applied during post-veraison, finding differences with respect to well-irrigated vines in the case of cv. Crimson, of 19.6% [10], 30% [9,20], and 35% [32].

Moreover, RDI requires not only the careful selection of the time of application but also of the intensity and duration of the application, which all depend on the stage of plant development [2]. In fact, RDI emerged as an irrigation strategy for controlling the excessive vigor shown by peach trees [6], and later proved to be an irrigation strategy that could save a large amount of water in different crops, while maintaining or improving the fruit quality at harvest [3].

Effectively, different authors have found the post-veraison stage to be a non-critical period for the crop when using deficit irrigation strategies for different table grape varieties [10,20,33], as a reduction in the water applied throughout the growing season can reduce the size of the berry, and therefore the total yield [9,10,17,34]. This also occurs with other deciduous species, in which a continuous water deficit during the entire cycle of the crop reduces the yield and even the size of the fruit [2,35].

Thus, Conesa et al. [9,20] achieved similar water reductions for cv. Crimson, which were even higher than those obtained in this work, without affecting yield, although due to the meteorological conditions, both post-veraison and harvest took place about 20 days later. The authors stated that these deficit irrigation treatments (RDI and PRD treatments, with similar values of annual volumes of water received) enhanced berry coloration, providing grapes that were more acceptable to consumers than the Control treatment [20]. PRD induced a greater accumulation of skin anthocyanins and resveratrol, while increasing the soluble phenolic content and antioxidant capacity evaluated at harvest [16]. Moreover, another benefit of PRD applications in table grapes is a higher control of vegetative growth as compared with RDI and fully irrigated (FI) vines, as reported by Çolak and Yazar [36] in Royal table grapes, who found lower values of total leaf area at harvest in the PRD treatment. This reduction was also observed in the PRD treatment of Crimson table grapes [37].

In our study, the vines subjected to PRD showed the most negative Ψ_s values than those from the RDI treatment, but the water stress level was more continuous and stable in the latter, as shown by the higher values of the water stress integral during the last two years studied (Figure 2). These values were smaller than those found by Conesa et al. [20], but were able to promote a certain precocity in the commercial maturity of the fruit (Figure 6). Although this strategy infers a better berry quality at harvest, as mentioned, it is difficult to implement it at a commercial level, because the placement of the drippers in the irrigation system has to be modified, which makes difficult the deficit irrigation scheduling [19,37].

Indeed, the sensitivity of table grape crops with regard to water deficit has been confirmed in the different works described above, in which irrigation was scheduled based on ET_C; however, Boini et al. [38] mentioned that it would be highly desirable to schedule irrigation based on the actual plant water status, as it changes depending on several tree-related factors such as rootstock, source/sink ratio, phenological stage etc. [39,40]. Jones [41] suggests that more integrative soil moisture measurements would be preferred to instantaneous measurements such as midday leaf water potential, although predawn leaf and stem water potential may be useful surrogates for soil water potential for irrigation scheduling. Stem water potential (Ψ_s) is probably the most reliable plant water status indicator [42], despite the difficulty in measuring it in commercial orchards. This measurement is obtained through a destructive technique, which is time-consuming and it is currently impossible to automate [43]. In our experiment, the anomalous values shown by the vines of the CTL treatment in pre-veraison in 2016 is even worth highlighting, with values around -0.72 MPa of Ψ_s, due to values of applied water (aprox. 80 m^3 ha^{-1}) below that applied during the first and third year (aprox. 170 m^3 ha^{-1}), for this same treatment.

As mentioned, the deficit irrigation treatments did not have a negative influence on the fruit quality, but as shown in the evolution of the Ψ_s and the size of the berry, an excessive water reduction can lead to its decrease (Figure 4). Indeed, it can be considered that a difference in pre- and post-veraison periods by an interval between 0.15 and 0.32 MPa with respect to well-irrigated vines, could be considered to be a threshold value to avoid this decrease, as Conesa et al. [9] found. Effectively, fruit water accumulation is highly sensitive to the level of water deficit during all the fruit developmental stages [3], as demonstrated via the strong correlations between mean Ψ_s values during the season and harvest fruit size [44]. In apple trees, Boini et al. [38] proposed fruit growth during the cell expansion stage, when fruit growth rates are constant [45], as a potential indicator of the plant water status, in order to implement this in decision support systems for irrigation scheduling. In this way, they found the onset of drought stress below the threshold of about 1.2 g fruit^{-1} day^{-1}, which corresponded to a midday stem water potential below -1 MPa. In apricots trees, Pérez-Pastor et al. [28] found that a plant water deficit of around 0.6 MPa of leaf water potential at predawn, with respect to Control values during stage III, promoted a decrease in fruit growth.

Therefore, it is necessary to provide farmers with irrigation scheduling protocols that are capable of adjusting the application of water to the availability of water in the irrigation communities without negatively affecting the fruit growth or the plant water status and minimizing the negative effects of mild water stress on yield and berry physico-chemical quality. Thus, Figure 8 proposes a weekly irrigation scheduling ranging from 140 to 340 m^3 ha^{-1} week^{-1}, in post-veraison, totaling 4000 and 7000 m^3 ha^{-1}, respectively, for the entire growing season, without negatively affecting yield, and maximizing the productivity of the available irrigation water.

Indeed, it has been found that the post-veraison period is a non-critical period in which a reduction in water can be applied to achieve significant water savings, although certain uncertainties would make the application of these strategies difficult, such as the timing of the start of the non-critical period, and how to not exceed the threshold values of the plant water status defined above. For this reason, a Gaussian process regression model was implemented to estimate the amount of water to be applied at each time depending on the developmental stage of the crop. This methodology has also been used to improve the accuracy in leaf area index (LAI) retrieval and to provide uncertainty estimates directly through Gaussian probabilities [46,47].

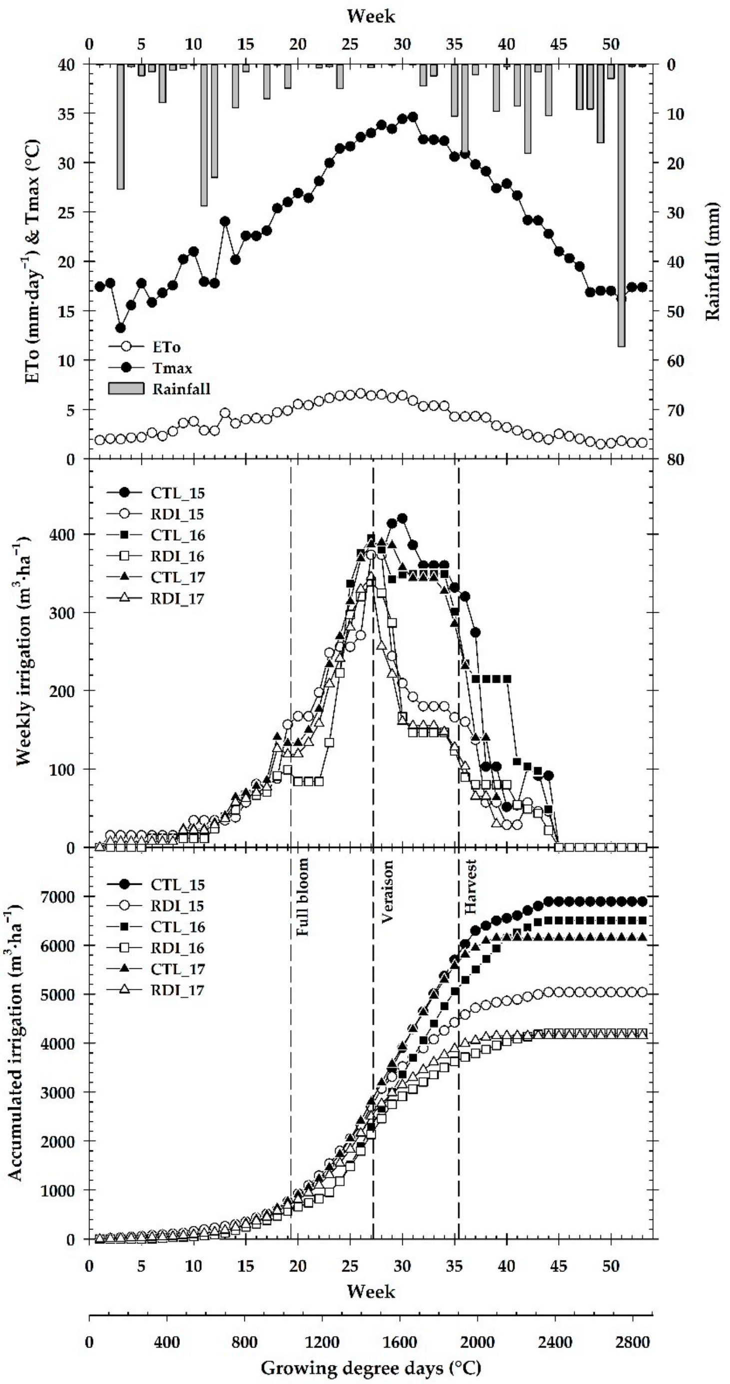

Figure 8. Average seasonal evolution of reference crop evapotranspiration (ET_0), vapor pressure deficit (VPD), temperature and rainfall during the three years assayed (2015–2017). Seasonal variation of irrigation water applied weekly and cumulative water applied, for CTL and RDI treatments: CTL (black circles, 2015; black squares, 2016; black triangles, 2017) and RDI (white circles, 2015; white squares, 2016; white triangles, 2017). The dashed lines indicate the full bloom, veraison and the harvest periods.

5. Conclusions

The post-veraison stage was revealed as a non-critical period for the application of regulated deficit irrigation strategies, increasing the water use efficiency values above 50% with respect to well-watered vines, and promoting a certain precocity in the commercial maturity of the berries. The berry size was also proven to be a very sensitive to deficit irrigation, decreasing in diameter with differences of 0.15 and 0.32 MPa with respect to well-watered-vines, in pre-veraison and post-veraison stages, respectively. Therefore, weekly deficit irrigation protocols are proposed for their use in semi-arid areas characterized by a high degree of uncertainty of water availability for irrigation, with a range from 140 to 340 m^3 ha^{-1} $week^{-1}$ in post-veraison, totaling 4000 and 7000 m^3 ha^{-1}, respectively, for the entire growing season. Likewise, in order to automate deficit irrigation, the onset of the post-veraison stage was defined based on the number of accumulated growing degree days, and the prediction of applied irrigation water based on the Gaussian process regression model by using the day of the year and maximum temperature of the day data as explanatory variables, obtaining a high coefficient of determination.

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