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Article

Response of Table Grape to Irrigation Water in the Aconcagua Valley, Chile

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Abstract: The irrigation water available for agriculture will be scarce in the future due to increased competition for water with other sectors, and the issue may become more serious due to climate change. In Chile, the table grape is only cultivated under irrigation. A five-year research program (2007–2012) was carried out in the Aconcagua Valley, the central area of grapes in Chile, to evaluate the response of table grape vines (*Vitis vinifera* L., *cv* Thompson Seedless) to different volumes of irrigation water. Four irrigation treatments were applied: 60, 88, 120 and 157% of crop evapotranspiration (ETc) during the first four years, and 40, 54, 92 and 108% of ETc in the last year. Irrigation over 90%–100% of ETc did not increase fruit yield, whereas the application of water below 90% ETc decreased exportable yield, berry size and pruning weight. For example, 60% ETc applied water reduced exportable yield by 20%, and only 40% of the berries were in the extra and large category size, while pruning weight was 30% lower in comparison to the treatment receiving more water.

Key words: table grape; water production function; berry size; grapevine irrigation

1. Introduction

Chile is one of the main exporters of table grapes in the world. There are 52,234 hectares dedicated to table grape cultivation, from the Atacama Region (30° S Latitude) to the Maule Region (36° S). The annual production of table grape was 725,000 tons in 2013/2014 [1]. The wide territorial extension of table grape cultivation means that it grows under different climatic conditions, ranging from desert in the north (30° S Lat.) to the Mediterranean climate between 30° and 40° S [2]. Annual mean precipitation varies from 22.8 mm in the north to 735 mm in the south; rainfall is concentrated mainly in the winter months [2]. Therefore, the table grape in the north must be grown under irrigation and the productivity depends upon the availability of water in spring and summer months. The Aconcagua Valley in Chile is one of the most important zones in the production of table grapes in the country, with 10,770 ha in full production annually. The most important cultivars are Thompson Seedless, Flame Seedless, Crimson Seedless and Red Globe [1]. Villagra *et al.* [3] measured a seasonal ETc (September to March) around 800 mm using the Eddy covariance technique. However, local farmers use a wide range of water volumes to irrigate table grapes, above or below 800 mm per growing season.

The availability of water for agriculture will be scarce in the future, due to increased competition for water with other sectors of the economy, and climatic change may lead to more recurrent drought situations [4,5]. In the area of table grape production in Chile (30° to 36° South latitude), there is evidence that precipitation has decreased in the last century; rainfall is predicted to decline 25%–35% by 2040–2070, and average temperature to increase by 2–4 °C [6,7] as a consequence of climate change. Furthermore, Chile is periodically affected by the El Niño-Southern Oscillation (ENSO), which leads to severe droughts (La Niña event) and economic losses [8]. This means less storage of water in the soil, less runoff to reservoirs and less recharging of aquifers. In addition, as a consequence of climate change the 0° isotherm will increase in altitude [6], and the area of snow reserves in the mountains for river water flow in spring and summer will decrease; therefore, irrigation water in the period of maximum crop development will be limited.

Crop production must be more efficient in the use of water [5]. Strategies are required to determine crop evapotranspiration (ETc) and irrigation needs [3], and using improved irrigation practices to reduce the quantity of water applied to crops without affecting yields or product quality [9]. Regulated deficit irrigation (RDI) and sustained deficit irrigation (SDI) have been used as strategies to reduce the volume of water applied without affecting yields [9]. With RDI, water is applied to crops below the ETc in specific phenological periods, and this technique has been shown to be successful in crops such as peach [10], olive [11,12] and wine grape [13,14].

With SDI technique, reduced water is applied to crops during the entire development period, independent of the plant physiological stage [9]. In some fruit crops, this technique has produced better results than RDI in terms of crop production and water saving [15]. There is sufficient evidence that supplying the full ETc requirements to tree crops and vines may not be necessary in many situations [16]. However, most of the experiments in vine grape have been on wine grapes and little on table grapes. Berry quality variables of table grapes differ from those of wine grapes. In table grape, berry size, firmness, color, acidity and total soluble solids are important quality parameters [17]. There are a few RDI studies with table grapes where an irrigation restriction was imposed after veraison when berries have almost reached full size [18–20]. El-Ansari *et al.* [19] showed that the cultivar "Muscat of

Alexandria" decreased firmness and acidity and increased total soluble solids of the berries under RDI. Ezzahouani and Williams [20] found that under different irrigation treatments the cultivar "Danlas" obtained the highest yield and berry weight under well irrigated treatments. Williams *et al.* [17,21] studied the effect of SDI on Thompson Seedless for raisin production, and concluded that application of water above 80% of the crop evapotranspiration (ETc) did not increase fruit yield, whereas below 60% ETc decreased berry yield and weight but increased soluble solids.

The aim of this study was to determine the effect of different amounts of irrigation on the yield and fruit quality of table grape in the Aconcagua Valley of Chile.

2. Materials and Methods

2.1. Experimental Site and Irrigation Treatments

The experimental site was located in a commercial table grape vineyard in the Aconcagua Valley, Valparaiso Region, Chile (70°41′23″ W, 32°47′21″ S). The soil is a Fluventic Haploxerolls, 1 m depth, with a clay loam texture in all depths. Annual rainfall and reference evapotranspiration (ETo) during the study period are presented in Table 1. The cultivar was Thompson Seedless on Freedom rootstock, trained as overhead trellis system and irrigated by drip (double line). The vineyards were planted in 2003, with a plant spacing of 3 × 2.5 m.

Table 1. Seasonal precipitation, seasonal reference evapotranspiration (ETo), seasonal crop evapotranspiration (ETc), applied water and percentage of ETc in each experimental year.

Season	Annual Rain	Season ETo	Season ETc	Applied water (m^3ha^{-1})				Percent ETc (%)			
	(mm)	(mm)	(mm)	T1	T2	T3	T4	T1	T2	T3	T4
2007/08	116.3	845.2	799.2	5279	7647	9705	11796	66	96	121	148
2008/09	242.9	876.4	741.4	4717	6388	9397	11217	64	86	127	151
2009/10	182.4	825.6	658.1	3597	5755	7865	10806	55	87	120	164
2010/11	141.8	870.18	690.18	3992	5782	8395	11498	58	84	122	167
2011/12	111.1	962.3	674.12	2663	3615	6171	7293	39	54	92	108

The experiment was performed during five years; in the four first seasons (2007/08 to 2010/11) four irrigation treatments were applied during the entire season; T1: 60% of crop evapotranspiration (ETc), T2: 88% ETc, T3: 120% ETc and T4: 157% ETc. In the last season (2011/12) less water was applied in all the treatments; 40, 54, 92 and 108% of ETc for T1, T2, T3 and T4, respectively. Each season, irrigation treatments were started on 1 October and finished on 31 March. The water applied each season and the resulting percentages of ETc are presented in Table 1. Each treatment was replicated four times in a randomized block design, each elementary plot contained 16 vines, and measurements were done only in the four central plants to avoid border effects. ETc was calculated as ETo × kc, where kc is the crop coefficient [22]. ETo was estimated by the Penman-Montheith method [22], using climatic data from an automatic weather station near the field experiment (www.agroclima.cl network). Crop coefficient (kc) was estimated following the methodology proposed by Villagra *et al.* [3] and Williams and Ayars [23]. Irrigation was scheduled in a low frequency regime as recommended by Selles *et al.* [24] for the fine-textured soil of the Aconcagua valley.

2.2. Soil and Plant Water Status

Soil water content and stem water potential (SWP) were measured throughout the entire season. Soil water content was measured daily with a capacitive probe (Diviner 2000, Sentek Inc., Sidney, Australia) with 10 cm increment down to the depth of 1 m. Seven access tubes were used in each treatment, placed 30 cm away from the plant row. The readings were expressed as total soil available water (SAW). To express soil water content measured with the capacitive probe as SAW, the soil was irrigated around the access tubes until field capacity (FC) was reached as proposed by Cassel and Nielsel [25]. After that, soil water content was measured with the probe and the value obtained was established as FC. In addition, the permanent wilting point was estimated as half of FC [26,27].

Midday stem water potential (SWP) was measured at midday (2–4 PM, solar time) every other week, before an irrigation event, using a pressure chamber technique [28]. Three leaves were used per replicate; the leaves were covered with an aluminized plastic bag one hour before being measured [29].

2.3. Vegetative Growth and Fruit Production

Each season, pruning weight was determined on four central plants per replicate (16 per treatment) and expressed as pruning dry matter. A sample of fresh pruned branches was dried at 70 °C in a forced-air oven for 48 h to determine the water content of the sample.

During each season, the intercepted solar radiation (ISR) by the vines was measured from bud break to harvest. At midday, the flux density of photosynthetically active incident radiation (PAR_i) over and under the orchard (PAR_{bd}) was measured with a ceptometer (AccuPAR, Decagon Devices, Washington, DC, USA). Data were measured in each replicate in one quadrant of four plants each. Fifteen measurements were made per quadrant; three in each row and five between rows. Mean of ISR (µmol m^{-2} s^{-1}) were expressed as percentage using:

$$ISR = \left[1 - \left(\frac{PAR_{bd}}{PAR_i}\right)\right] \times 100 \quad (1)$$

After fruit set, the number of bunches per vine and the number of berries per bunch were defined as in normal commercial table grape management. (40 ± 2 bunches per vine and 113 ± 10 berries per bunch). At harvest, exportable fruit production was measured in the four central plants per replicate. All harvested export bunches were weighed, and a random sample of 100 berries per replicate (400 per treatment) were weighed individually. A sample of bunches was commercially packed and stored at 0 °C and 90% relative humidity for laboratory analysis; berry firmness was measured with 200 berries with attached pedicel per treatment using a FirmTech 2 apparatus (BioWorks Wamego, KS, USA), along with soluble solids, juice acidity and shatter.

2.4. Statistical Analysis

Data were subjected to analysis of variance using MIXED model, and mean separation was performed by the LSD method or Duncan's multiple range test where appropriate (SAS Institute Inc., Cary, NC, USA).

3. Results and Discussion

The volume of water applied in each treatment from bud break until the end of maturity is shown in Table 1. Winter precipitation was sufficient to maintain the soil available water (SAW) close to field capacity (FC) until bud break time each year. The irrigation treatments produced a reduction of SAW during the season (Figure 1) in the treatments which received less water (T1 and T2). Accordingly, a moderate water deficit was produced and reflected in SAW (Table 2) and SWP (Table 3).

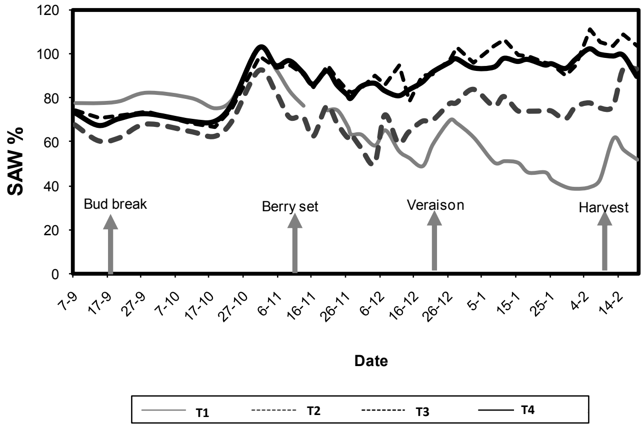

Figure 1. Typical variation of soil available water (SAW%), during the 2007/08 season. Arrows indicate different phenological stages.

Table 2. Average soil available water (SAW%) in each experimental year.

Irrigation Treatment	2007/08		2008/09		2009/10		2010/11		2011/12	
	S-V*	V-H*	S-V	V-H	S-V	V-H	S-V	V-H	S-V	V-H
T1	63.73	64.4	60.32	54.45	86.2	56.21	90.91	66.68	83.88	41.77
T2	70.9	73.8	67.29	67.93	70.9	63.81	91.55	72.16	75.65	48.15
T3	79.35	81.75	75.07	77.69	85.95	73.91	80.48	79.14	84.8	88.85
T4	81.22	93.17	78.36	81.73	98.46	88.73	89.59	84.68	85.73	82.9

*(S-V bud break to veraison, V-H, veraison to harvest).

Table 3. Average stem water potential (SWP, MPa) in each experimental season.

Irrigation treatment	Fruit set-Veraison (MPa)					Veraison-Harvest (MPa)				
	2007/08	2008/09	2009/10	2010/11	2011/12	2007/08	2008/09	2009/10	2010/11	2011/12
T1	−0.64 c	−0.78 b	−0.73 b	−0.63	−0.88 c	−0.71	−1.00 b	−0.96 b	−0.83	−1.16 c
T2	−0.62 bc	−0.76 a	−0.73 b	−0.64	−0.79 b	−0.67	−0.88 ab	−0.83 a	−0.86	−0.98 b
T3	−0.59 ab	−0.76 a	−0.63 a	−0.62	−0.72 a	−0.66	−0.87 ab	−0.80 a	−0.77	−0.81 a
T4	−0.53 a	−0.68 a	−0.63 a	−0.60	−0.68 a	−0.63	−0.82 a	−0.77 a	−0.83	−0.80 a

Means followed by a different letter within a given year are significantly different at $P < 0.05$

Allen *et al.* [22] established that soil water depletion greater than 30% of SAW (<70% SAW in the soil) is a critical point for table grapes. In this study, only T1 and T2 presented SAW below 70% in the soil, mostly from veraison to harvest. In Thompson Seedless, SWP at midday below −0.9 MPa was defined as moderate water stress by Selles *et al.* [24]. Grimes and Williams [30] consider –1 Mpa as the threshold value. From this point of view, only T1 was subjected to a moderate water stress between veraison and harvest. The average water received by T1 was only 60% of ETc (2007/2008 to 2010/11) and 39% of ETc in the last season (2011/12); a severe water stress was not observed. As all treatments in each season began with the SAW close to FC (Table 2), part of the water used by plants in the T1 treatment came from the soil, preventing severe plant water stress during the season (Figure 1).

Irrigation treatments had an effect on winter pruning weight; the differences between T1 and T4 were significant in three out of the five experiment years; plants which received less water showed lower pruning weight (Table 4). A linear relationship was found between applied water (% ETc) and the relative pruning weight of the vines ($r^2 = 0.67$, Figure 2). For the same cultivar, Williams *et al.* [21] found also a linear relationship between pruning weight and SWP at midday. This relationship shows that vine pruning weight is sensitive to moderate water stress.

Table 4. Winter pruning dry weight (kg plant^{-1}) and average solar radiation intercepted by the vines (ISR, %) from veraison to harvest.

Irrigation treatment	Pruning dry weight (kg plant^{-1})					ISR (%) from veraison to harvest				
	2007/08	2008/09	2009/10	2010/11	2011/12	2007/08	2008/09	2009/10	2010/11	2011/12
T1	1.82 b	1.61 b	2.47	2.16	2.11 b	80.55	87.53	85.35	84.47 a	81.7 c
T2	2.04 ab	2.01 ab	2.51	2.07	2.08 b	76.93	84.13	84.34	83.52 a	85.72 bc
T3	2.34 ab	2.20 ab	2.97	2.24	2.92 a	84.2	89.58	89.95	90.54 ab	90.54 ab
T4	2.89 a	2.46 a	3.18	2.5	3.17 a	83.2	86.53	88.26	81.13 a	92.53 a

Means followed by a different letter within a given year are significantly different at $P < 0.05$.

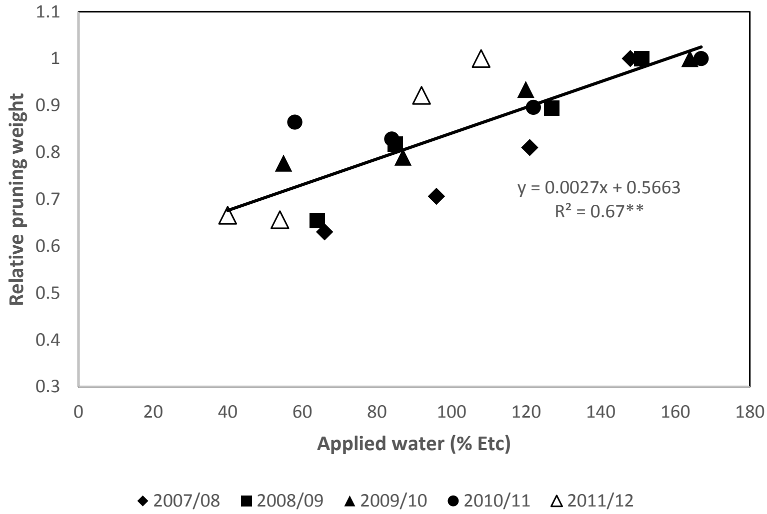

Figure 2. Relationship between applied water (% ETc) and relative winter pruning weight in the different experimental seasons.

ISR was similar in all treatments in four of the five years of the experiment, but in 2011/12, T1 treatment which received only 39% ETc, presented significant differences in ISR compared to the other treatments (Table 4). That year the SAW and SWP of T1 were lower than in other years between veraison and harvest (Tables 2 and 3), which clearly affected vine vegetative growth (Table 4). Similar results were found also in Thomson Seedless [21], where sustained deficit irrigation reduced leaf area and pruning weight per vine compared to vines irrigated at 100% ETc.

In 2011/2012, SWP decreased below −1 MPa, showing a moderate water stress in T1. Selles *et al.* [31] also showed that vegetative growth is affected by the amount of water applied in Crimson Seedless cultivar growing in the Aconcagua Valley. That study also reported that water applied affected not only pruning weight but also trunk growth. Willians *et al.* [21] also showed that vegetative growth (shoot length, pruning weight and leaf area) of Thomson Seedless is affected by the amount of water applied.

The volumes of water applied produced a significant decrease in the mean bunch weight in four of the five years; T1 average bunch weight was less than T3 and T4. Berry weight was also affected by the amount of water (Table 5). The percentage of extra and large berries (>5.2g) increased with increasing water applied (Figure 3).

Table 5. Bunch and berry weight at harvest (g) in each treatment, in five experimental seasons.

Irrigation treatment	Bunch weight (g)					Berry weight (g)				
	2007/08	2008/09	2009/10	2010/11	2011/12	2007/08	2008/09	2009/10	2010/11	2011/12
T1	607.5 b	623.2 b	578.5 b	560.7	511.1 b	4.76 c	4.86 b	5.19 b	5.28	5.5 b
T2	650.9 ab	676.9 ab	618.8 ab	625.4	528.0 ab	5.08 bc	5.02 b	5.17 b	5.39	6.0 ab
T3	674.6 ab	729.7 a	661.7 a	671.8	549.4 ab	5.67 ab	5.49 a	5.56 ab	5.48	6.11 ab
T4	714.4 a	723.2 a	682.9 a	631.9	594.0 a	5.85 a	5.64 a	5.74 a	5.44	6.23 a

Means followed by a different letter within a given year are significantly different at $P < 0.05$.

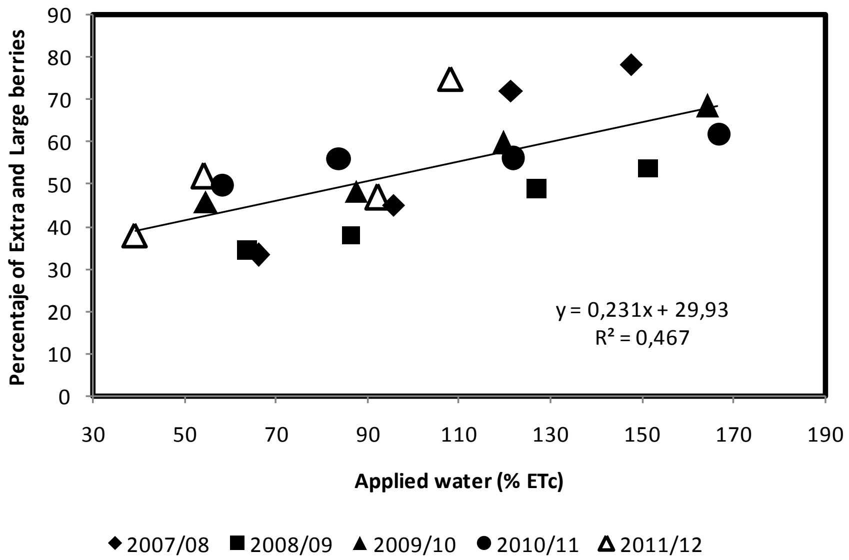

Figure 3. Relationship between percentage of Extra and Large berries and percentage ETc of water applied in the different experimental seasons.

Williams *et al.* [17], using Thompson Seedless cultivar grown for raisins, found a linear relationship between SWP and berry weight at harvest; berry weight increased with increased water applied up to 80% ETc, while more water beyond 80% ETc did not produce greater berry weight. This relationship was also linear in the present study, even for greater amounts of water. The difference may be due to the fact that there are fewer berries per bunch in table grape than in raisin production, thus the berries may grow more when there is less competition within the same bunch. In table grape, berry size is a very important commercial quality component; extra and large sizes have better market prices and it is very important for the grower that most of the bunches have these berry sizes. Other quality parameters are: color (green color in the case of Thompson Seedless), berry firmness, sugar content and juice acidity. In this study, the application of less water (e.g., 40% ETc in 2011/2012) affected the percentage of green berries in bunches due to more solar light received by bunches in T1, with lower intercepted solar radiation (Figure 4). This agrees with the results of Selles *et al.* [32], who found that with less than 80% ISR there was a predominance of yellow color in this cultivar.

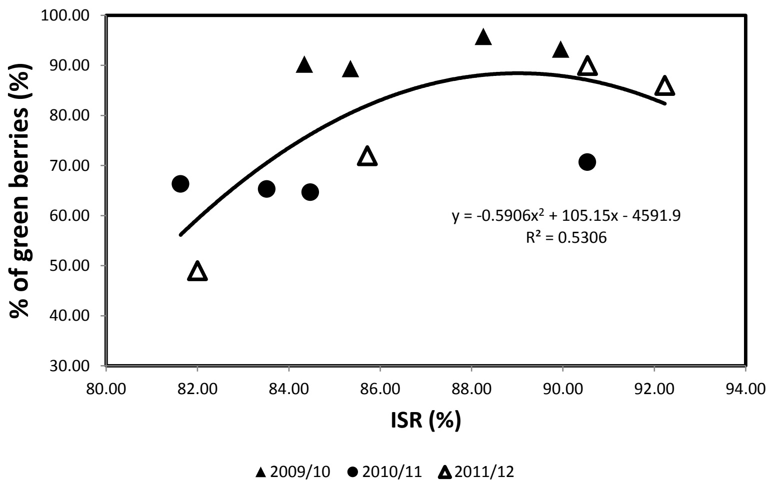

Figure 4. Percentage of green commercial berries per bunch as a function of intercepted solar radiation (ISR, %) in the different experimental growing seasons.

The quality parameters firmness (Table 6) and sugar content (Table 7) were not affected by the irrigation treatment in any experimental year, and were in the normal range for this cultivar [33]. Williams *et al.* [17] found an increase in berry sugar with water application under 60% of ETc in Thompson Seedless for raisins. However, juice acidity was between 0.7 and 0.8 mg of tartaric acid/100 mL juice in all years and treatments; these are considered normal values for this variety [33]. Also, shattering was very low (less than 1.7%) in all treatments and all years. In summary, the only quality parameters affected by irrigation treatment were berry size and berry color (lower percentage of green berries in the bunch).

Table 6. Berry firmness at harvest (g mm^{-2}) in each treatment, in five experimental years.

Irrigation treatment	Berry firmness (g/mm^2)				
	2007/08	2008/09	2009/10	2010/11	2011/12
T1	282.1 b	235.5 b	262.9	283.3 ab	258.2
T2	298.4 ab	242.2 b	275.6	279.7 b	274.7
T3	304.6 ab	261.8 ab	290.4	320.5 a	272.7
T4	327.3 a	275.3 a	294.2	313.5 ab	275.1

Means followed by a different letter within a given year are significantly different at $P < 0.05$.

Table 7. Berry sugar content at harvest (ºBrix), in each treatment, in five experimental seasons.

Irrigation treatment	Sugar content (°Brix)				
	2007/08	2008/09	2009/10	2010/11	2011/12
T1	18.97	20.5	17.39	21.45	21.08 a
T2	18.21	18.23	17.34	21.92	21.06 a
T3	18.38	18.98	17.61	21.31	20.95 ab
T4	18.84	19.35	17.43	21.79	20.43 b

Means followed by a different letter within a given year are significantly different at $P < 0.05$.

Finally, a production function was established correlating relative yield (actual treatment yield/maximum yield) to water applied in terms of percentage of ETc (Figure 5).

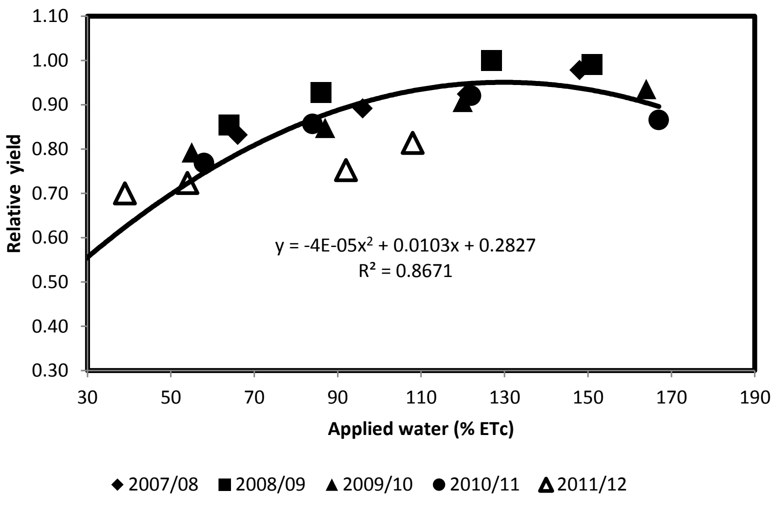

Figure 5. Relative yield as a function of applied water (% ETc). Relative yields represent the yield of each treatment divided by the highest yield recorded.

Relative yield increased by 30% when applied water increased from 40%–100% of ETc, and above this amount relative yield did not increase (Figure 5). Williams *et al.* [17], in Thompson Seedless destined to raisin production, found that yield increased when water applied was increased up to 80% ETc. A linear relationship between water applied and relative yield of Crimson Seedless cultivar in the Aconcagua Valley was reported by Ferreyra *et al.* [34]; the exportable production increased by 22%

when the water applied was increased from 40%–100% of ETc. Netzer *et al.* [35] in Superior cultivar in Israel found that yield decreased by 29% when water application was reduced from 100%–40% of ETc. Similar results were found by Vita *et al.* [36] in Argentina, also in the Superior cultivar. In our case, it is interesting also to consider that berry size decreased as applied water was reduced (Figure 3). That means that a reduced amount of water not only decreases total yield but the berry size, affecting commercial quality.

Water use efficiency (WUE), defined as kilograms of fresh fruit per cubic meter of applied water, increased as applied water decreased, from 2.3 (160% ETc) to 7 kg m a^{-3} (40% ETc) (Figure 6). Deficit irrigation (RDI or SDI) has been proposed as one way to increase water use efficiency particularly for woody perennial crops [9]. However, in our case increasing WUE over 3.7 kg m^{-3} the fruit commercial quality diminished. Thompson Seedless for table grape production has high sensitivity to water deficit when quality standards are considered. SDI below 80%–90% ETc is not recommended, at least before harvest.

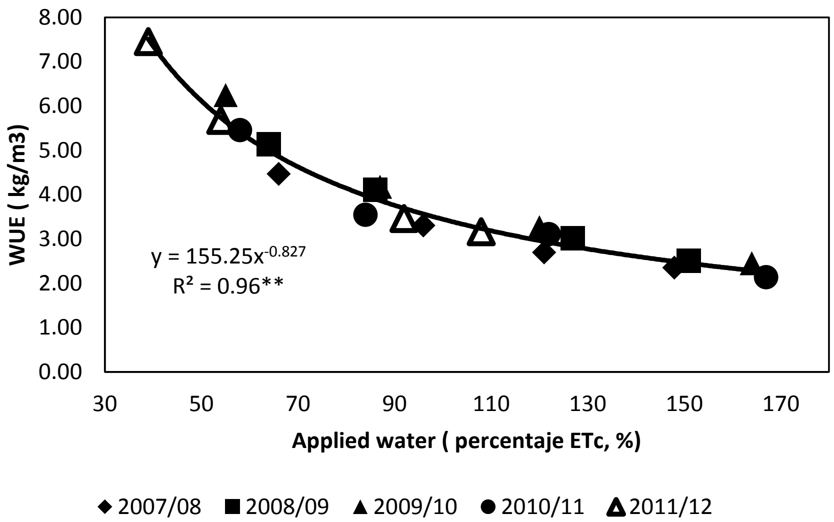

Figure 6. Water use efficiency (kg of fresh fruit per cubic meter of applied water, kg m^{-3}) as a function of applied water (% ETc).

4. Conclusions

Irrigation water above 90%–100% ETc did not increase fruit yield in table grapes, whereas the application of water below 90% ETc decreased exportable yield and fruit quality as reflected by smaller berry size and a greater proportion of yellow fruit. Irrigation amounts did not have a significant effect on the other quality parameters such as firmness, sugar content and juice acidity. Pruning weight was also affected when less water is applied, reducing shoot wood for future vine fructification, compromising sustainable grape production. The SDI technique on table grapes could be used as a short term strategy to avoid water scarcity, but not as a permanent or long term strategy, at least in the Thomson Seedless cultivar. In this cultivar, it is better to irrigate a smaller surface with adequate amounts of water, so the yield and quality of the fruit are not affected.

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Authors Contribution

Gabriel Selles was responsible of the all research project and with Raúl Ferreyra were responsible for the interpretation of results and manuscript preparation. Carlos Zuñiga and Cristina Aspillaga were responsible for technician supervision and all phases of field operations, measurements and statistical analysis

Conflicts of Interest

The authors declare no conflict of interest.

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