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Effects of moderate irrigation on vegetative growth and productive parameters of Monastrell vines grown in semiarid conditions

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Abstract

This study compares the vegetative growth and productive parameters of non-irrigated Monastrell vines with those under two moderate irrigation treatments. Plant water status and gas exchange parameters were used to evaluate the effect of moderate irrigation on the physiological status of the plants. The predawn and midday leaf water potentials were significantly lower in non irrigated vines, reaching values that indicated severe water stress. Stomatic conductance decreased as the season progressed, especially in non-irrigated vines. This stomata closure resulted in lower net photosynthesis, which affected vegetative growth and productivity. Non-irrigated vines developed a very small canopy and pruning weight together with a very low production compared with irrigated vines. The results demonstrate that the improvement in the physiological status of plants, with moderate irrigation leads to higher yield together with an equilibrium in the vegetative/reproductive growth.

Key words: grapevines, photosynthesis, stomatal conductance, water potential, production, yield, leaf area.

Resumen

Efecto del riego moderado en el crecimiento vegetativo y en los parámetros productivos de viñas Monastrell cultivadas en condiciones semiáridas

Este estudio compara el crecimiento vegetativo y los parámetros productivos de vides Monastrell en secano y otras con dos tratamiento de riego. Para evaluar el efecto del riego en la planta, se midieron los potenciales hídricos al alba y al mediodía y los parámetros de intercambio gaseoso. Los potenciales hídricos fueron significativamente menores en plantas en secano, alcanzando valores que indican un fuerte estrés hídrico. La conductancia estomática decreció al avanzar la estación, especialmente en viñas en secano. El cierre estomático se tradujo en una fotosíntesis neta menor, lo que afectó al desarrollo vegetativo y al rendimiento. Las viñas en secano desarrollaron una masa foliar muy pequeña y un peso de poda muy bajo. Los resultados demuestran que la mejora del estado hídrico de las plantas condujo a producciones mayores y a un correcto balance entre el desarrollo vegetativo y productivo.

Palabras clave: vides, fotosíntesis, conductancia estomática, potencial hídrico, producción, área foliar.

Introduction

Vineyard water management is considered an important tool for improving vine growth and fruit quality. Where vineyards have access to a permanent and unlimited water source, irrigation can be managed so that water stress is imposed during certain periods of time to increase fruit quality and to control canopy. This type of irrigation is often referred to as regulated deficit irrigation. However, in regions where water is usually a scarce and valuable resource, its use needs to be carefully managed for improving yield and avoiding severe water stress (Sipiora and Lissarrague, 1999; Rodrigues *et al.*, 2000).

Grape production depends on achieving an optimal growth of leaves and shoots needed to produce carbohydrates for the development and correct ripening of the clusters. Too much early stress will inhibit the development of the desired leaf to fruit ratio and the

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vine will not have the capacity to properly ripen the fruit (Lakso and Pool, 2000). Also, anything that limits leaf function will affect vine physiology and productivity (Poni *et al.*, 1994a).

Another effect of water stress is that it can reduce leaf photosynthesis. This effect is mainly due to stomata closure, restricting transpirational losses during periods of high atmospheric demand. This strategy helps to increase water use efficiency (WUE) but affects CO_2 uptake and reduces carbon assimilation (Lopes, 1999; Rodrigues *et al.*, 2000)

Due to the detrimental effects of water stress on grape, must and wine quality, the effect of moderate irrigation doses on a Monastrell (the second most common red grape cultivated in Spain) vineyard in S.E. Spain was studied, to assess the effect of two irrigation regimes, as compared with one non-irrigated treatment, on plant water status, gas exchange parameters, vegetative growth and production parameters.

Material and Methods

A Monastrell vineyard located within the Appellation of Origin Jumilla (Spain) was selected for the study (lat 38º 23'40'' N, long 1º 25'30'' W). Soils were 60 cm deep and the texture was determined as clay-loam. The training system was a bilateral cordon trellised to a three-wire vertical system. The vineyard was planted in 1997 on 1103 Paulsen rootstock. Planting density was 2.5 m between rows and 1.25 m between plants. Six two-bud spurs were left at pruning time. The experiment was carried out in 2000 and 2001.

The average annual temperature of this area is 15.5-16°C, while frost occurs on 25-35 days per year. The maximum temperature exceeds 30°C on 90 days, average annual rainfall is 290 mm and evapotranspiration accounts for 830 mm (a water deficit of 540 mm). Climatic data are shown in Table 1.

Two drip irrigation treatments (T1 and T2, water supply of 1,073 and 1,622 $m^3 ha^{-1} year^{-1}$, respectively) and a non-irrigated control (NI, no water was supplied) were imposed, starting on 15 April and ending on 31 October. Different irrigation programs were applied: from budburst to fruit set (April 15th to June 15th), and from veraison to harvest (August 15th to October 1st) vines were irrigated twice a week; from fruit set to veraison (June 15th to August 15th, vines were irrigated three times a week) (Table 2).

There was one emitter per plant with a delivery rate per emitter of 4 L h^{-1}. The design was a randomised complete block design with four replications. Each elementary vineyard plot contained 165 vines (512 m^2).

ET_0 was calculated from the mean values of the preceding 12 years following the method described by Pruitt (1986) using the data collected in the meteorological station located in the same vineyard. Vineyard evapotranspiration (Et_{vine}) was estimated using a varying crop coefficient (K_c) estimated for different conditions (Doorenbos and Pruitt, 1977; Grimes and Williams, 1990; Evans *et al.*, 1993). Crop coefficients were based

Table 1. Climatic conditions during 2000 and 2001 in the area of study

Year	Month	Temperature (°C)			Humidity (%)			Rainfall (mm)		Solar radiation (w m^{-2})	ET_o (mm)	Water supply (mm)	
		Mean	Max	Min	Mean	Max	Min	Total	Max	Mean	Mean	T1	T2
2000	Apr.	13.6	18.8	9.8	56.5	95.2	37.4	26.8	14.6	265.1	144	5	10
	May	18.3	25.0	13.1	65.8	91.4	42.1	55.0	38.8	300.5	172.4	11	23
	Jun.	22.2	28.9	17.3	51.8	76.9	25.8	1.8	1.4	369.9	232.5	21	35
	Jul.	24.9	29.3	21.1	47.2	67.3	31.5	11.3	11.3	358.7	238.1	33	50
	Aug.	24.6	28.0	21.1	47.0	81.4	24.4	16.7	16.6	305.1	206.7	20	28
	Sep.	21.0	24.3	16.4	62.0	84.0	30.8	13.4	10.2	256.3	143.7	14	14
2001	Apr.	14.9	19.6	10.8	54.6	95.0	30.5	25.1	18.8	300.1	157.8	5	10
	May	17.0	22.2	9.9	63.6	94.7	41.0	53.6	17.8	300.1	163.4	11	23
	Jun.	23.5	29.0	18.5	43.0	75.2	18.0	2.8	1.9	374.0	241.8	21	35
	Jul.	24.7	27.7	21.1	47.3	71.2	23.1	0.5	0.5	346.0	239.3	33	50
	Aug.	25.4	28.4	23.2	53.8	77.8	33.4	3.2	3.0	307.2	201.2	20	28
	Sep.	20.9	24.4	16.7	70.9	92.3	42.4	51.3	21.1	234.7	127.2	14	14

T1, T2: treatments as explained in Material and Methods.

Table 2. Crop coefficient (k_c) and water supply ($m^3\ ha^{-1}$)

Date	T1		T2	
	K_c	$m^3\ ha^{-1}$	K_c	$m^3\ ha^{-1}$
(15/4-15/6) Two irrigations per week	0.1	235	0.2	470
(16/6-15/8) Three irrigations per week	0.2	624	0.3	938
(16/8-1/10) Two irrigations per week	0.1	214	0.1	214
Total		1,073		1,622

on those proposed by Yañez *et al*. (1996). To apply crop coefficient (K_c) we divided the season into three periods. The crop coefficient and the irrigation data are presented in Table 2.

Leaf water potential was determined for fully exposed and expanded young leaves, which showed no visible signs of damage, using a portable pressure chamber (model Soil Moisture Equipment Corporation, CA, USA). Each leaf was covered with a plastic bag, immediately excised at the petiole and sealed into the humidified pressure chamber. Three leaves were sampled per plot (12 leaves per treatment).

Stomatal conductance (gs) and net CO_2 assimilation (A) were measured with a LCA4 (ACD Bioscientific, England) using exposed, fully expanded leaves from the mid-portion of shoots. Three leaves were sampled per plot (12 leaves per treatment) and measurements were done at 9:00 am.

The growth of shoots and node number was determined weekly selecting 8 shoots per treatment. Pruning weight was determined during the dormant season for 8 vines per treatment.

Leaf area per vine (12 measurements per treatment) was measured using the non-destructive method described by Dry (1997), separating leaves from main shoots and lateral shoots and using a leaf area meter (LICOR LI-3000). Leaf area was estimated by developing a second-order polynomial equation, relating vein length to leaf area.

Grapes from vines for the different treatments were harvested at approximately 22°Brix, recording at the same time the number of clusters per vine, total crop weight, number of berries per cluster, cluster weight and berry weight.

Table 3. Predawn leaf water potential

Year	Date	Predawn water potential (MPa)		
		NI	T1	T2
2000	15/6	–0.79 c	–0.68 b	–0.57 a
	27/7	–1.27 b	–0.89 a	–0.89 a
	10/8	–1.49 c	–1.10 b	–0.99 a
2001	13/6	–0.69 b	–0.58 a	–0.55 a
	4/7	–0.87 c	–0.77 b	–0.66 a
	8/8	–1.23 c	–0.87 b	–0.74 a

NI, T1 and T2: treatments as explained in Material and Methods. Different letters within the same row mean significant differences ($p < 0.05$) according to a LSD test.

Results

Plant water status (Ψ), gas exchange parameters at three different moments of the vegetative cycle

Predawn plant water potential (Ψpd) decreased during the season. Small differences in Ψpd were found on the first date (Table 3), with no significant differences between the irrigated treatments in 2001. As season progressed, the Ψpd decreased, specially in NI vines. At the beginning of August (veraison), the three treatments were significantly different, with a clear differentiation between irrigated and non irrigated vines, NI vines reaching values of around –1.5 Mpa in 2000 and –1.2 Mpa in 2001, compared with –0.9 and –0.7 MPa in T2 vines. The low Ψpd values reached by NI vines reflected the severe water deficit that these vines were suffering.

Midday leaf water potential (Ψmd) was higher in irrigated vines than non irrigated vines (Table 4), with

Table 4. Midday leaf water potential (MPa)

Year	Date	Midday water potential (MPa)		
		NI	T1	T2
2000	15/6	–1.57 b	–1.58 b	–1.43 a
	27/7	–1.70 c	–1.55 b	–1.41 a
	10/8	–1.93 b	–1.67 a	–1.65 a
2001	13/6	–1.47 b	–1.37 a	–1.36 a
	4/7	–1.74 b	–1.71 ab	–1.65 a
	8/8	–1.92 b	–1.76 a	–1.70 a

NI, T1 and T2: treatments as explained in Material and Methods. Different letters within the same row mean significant differences ($p < 0.05$) according to a LSD test.

Table 5. Net phothosynthesis (A), stomatal conductance (gs) and transpiration (E) measured at 9:00 am

Year	Date	A (μmoles m^{-2} s^{-1})			gs (mol m^{-2} s^{-1})			E (mmol m^{-2} s^{-1})		
		NI	T1	T2	NI	T1	T2	NI	T1	T2
2000	15/6	8.23 a	10.93 b	13.43 c	0.070 a	0.101 b	0.135 c	2.05 a	2.68 b	3.17 c
	20/7	6.35 a	11.39 b	13.33 c	0.051 a	0.104 b	0.131 c	1.48 a	2.46 b	2.74 b
	10/8	5.47 a	10.05 b	11.33 c	0.040 a	0.090 b	0.103 c	1.25 a	2.23 b	2.44 b
2001	14/6	7.74 a	11.26 b	11.50 b	0.063 a	0.104 b	0.110 b	2.22 a	3.22 b	3.24 b
	5/7	5.57 a	7.27 b	8.24 b	0.040 a	0.067 b	0.073 b	1.53 a	2.28 b	2.48 b
	19/8	6.21 a	8.93 b	11.16 c	0.043 a	0.076 b	0.096 c	1.25 a	1.91 b	2.15 c

Different letters within the same row mean significant differences ($p < 0.05$) according to a LSD test.

no differences between irrigated treatments. Very low values of this potential were found since vines from the T2 treatment showed values of around –1.4 MPa at the beginning of both years, while T1 and NI vines had values close to –1.6 MPa in 2000. These values became more negative and on the last sampling date, the evaporative demand was so high that even irrigated vines showed very low water potential, lower than –1.65 MPa and –1.7 MPa in 2000 and 2001 respectively.

The measurements of the gas exchange parameters were made at 9:00 am (7:00 am solar time), when the photosynthetic activity was found to be maximum. Large differences in the gas exchange parameters (A, g_s and E) between irrigated and NI vines were found (Table 5), the lowest values corresponding to NI vines.

It must be remembered that the observed reductions in gas exchange parameters cannot be attributed to the age of the leaves because in each measurement, the last fully expanded leaf was chosen, so the reductions might have been caused by decreases in water potential or less favourable environmental conditions as the season advances.

Vegetative growth

The water deficit suffered by non irrigated vines inhibited the maximum shoot growth rate and maximum node production (Fig. 1 and 2). The shoots of stressed vines grew less rapidly and ceased to grow earlier, while irrigation stimulated shoot growth. NI vines showed the shortest shoots. The longer shoots obtained in 2001 were probably due to the better plant status that year.

The number of nodes was significantly higher in irrigated vines but no differences were seen between the vines under irrigated treatments.

The differences in shoot length due to irrigation is reflected in total vine leaf area, measured in 2001 on two different dates (Table 6). In June, the leaf area of non irrigated vines was significantly lower than in the irrigated treatments. The area decreased at harvest being the leaf area of T2 vines twice that of non irrigated vines and significantly different from T1. The total leaf area of non irrigated vines in September was less than 1.3 m^2 per vine.

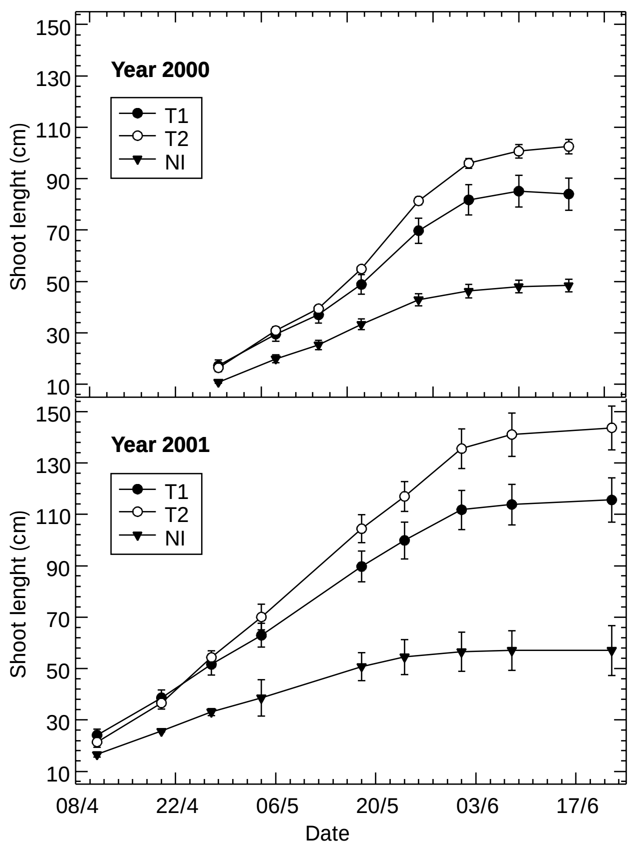

Figure 1. Evolution of shoots growth.

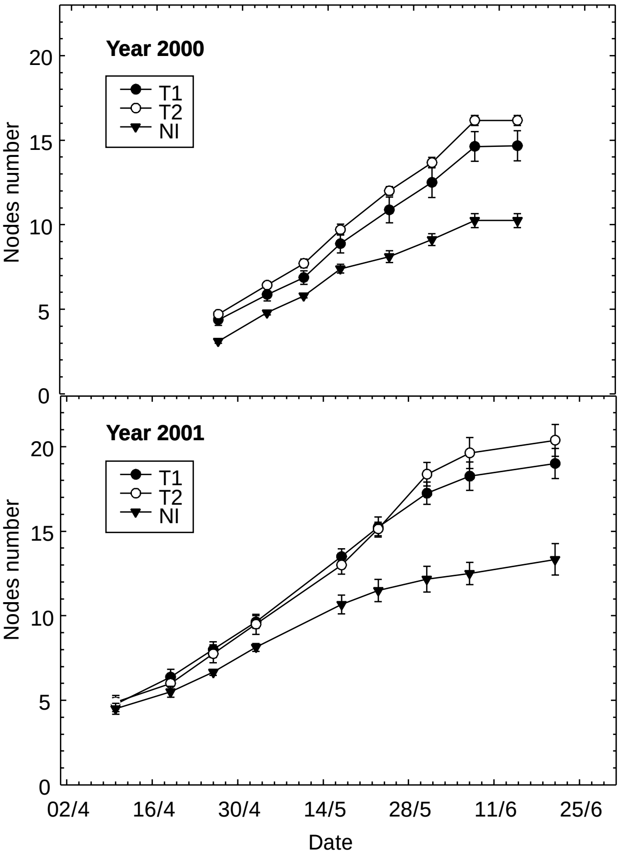

Figure 2. Number of nodes.

Figure 3 shows the percentages of primary and lateral leaves. In June, primary leaves accounted for 67% total leaf area in T1, 72% in T2 and 75% in NI vines. T2 vines, with a leaf area of 2.86 m^2 per vine in primary shoots showed the most developed canopy whereas NI vines, with 1.92 m^2 per vine had the lowest.

Primary leaf area represented in September 73%, 56% and 55% in T1, T2 and NI respectively. The results showed differences in leaf distribution from June to September, the relevance of the axial leaves increasing in T2 and NI vines the last date.

Table 6. Total leaf area measured in June 21st and September 6th, 2001, for the three irrigation programs

Irrigation program	June	September
	Total leaf area (m^2 per vine)	**Total leaf area (m^2 per vine)**
T1	3.81 b	1.73 a
T2	3.94 b	2.82 b
NI	2.55 a	1.23 a

Different letters within the same row mean significant differences ($p < 0.05$) according to a LSD test.

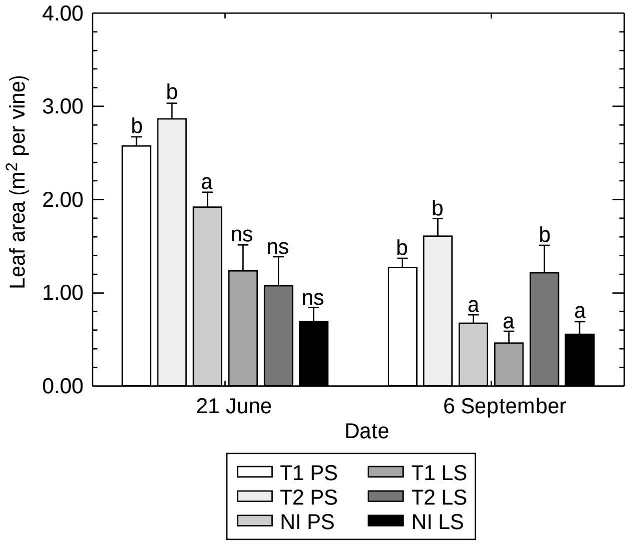

Figure 3. Leaf area in primary (PS) and lateral shoots (LS). Between columns, different letters express statistical significance ($P < 0.05$). ns: not significant.

Productive parameters

Average yield, cluster weight, clusters per shoot and berries per cluster are presented in Table 7. Irrigation significantly increased yield, vines from the T2 treatment having significantly higher yield than

Table 7. Mean values of the productive parameters of the non-irrigated vines and those irrigated with two different water doses

Productive parameter	Year	NI	T1	T2
Yield (kg per vine)	2000	0.86 a	1.90 b	3.32 c
	2001	0.90 a	1.82 b	2.56 c
Clusters per vine	2000	15.87 a	18.00 a	21.53 b
	2001	11.83 a	14.28 bc	15.78 c
Berries per cluster	2000	87.98 a	109.23 b	121.26 b
	2001	95.46 ns	115.90 ns	123.74 ns
Cluster weight (g)	2000	55.18 a	105.49 b	154.45 c
	2001	76.19 a	127.94 b	162.23 c
Berry weight (g)	2000	0.63 a	0.97 b	1.27 c
	2001	0.80 a	1.10 b	1.34 c

Different letters within the same row mean significant differences ($p < 0.05$) according to a LSD test. ns: not significant.

those from the T1 treatment, while non-irrigated vines produced the lowest yield. However, since only moderate water doses were supplied, the yield was not very high, even in irrigated vines. T2 vines produced the greatest number of clusters per vine although the differences from the other irrigated treatment were not always statistically significant. The number of berries per cluster and berry weight was greatest in T2 vines and T2 cluster weight was double that of non-irrigated vines and significantly higher than cluster from T1 vines.

Pruning weight (Fig. 4) was also reduced by water deficit. In 2000 the pruning weight of T2 vines doubled the pruning weight of NI vines and the difference was even higher in 2001. T1 vines showed intermediate values.

Discussion

The predawn leaf water potential (Ψpd) measures plant water status at zero plant water flux and provides information of the root zone soil water potential, because predawn plant water status is considered to be in equilibrium with soil water status (Choné *et al.*, 2001). Hence, leaf water potential has been used as an indicator of plant water status, assuming that there is no osmotic regulation, although when water stress develops, vine leaves have the ability to accumulate solutes, decreasing the osmotic potential and allowing the plant to maintain a positive turgor as Ψ becomes more negative (Lopes, 1999).

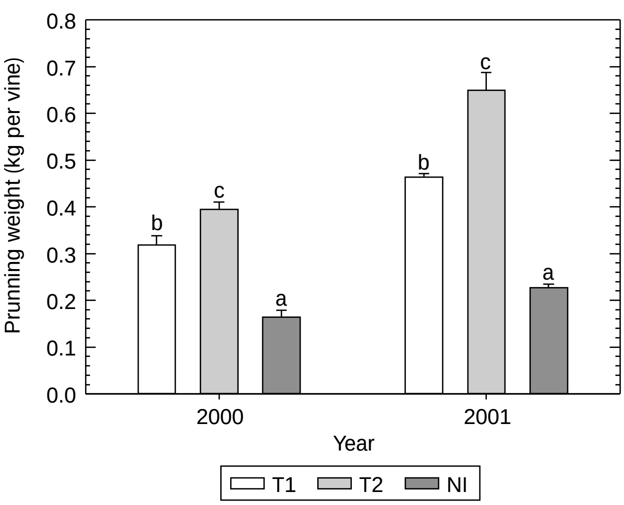

Figure 4. Pruning weight.

Previous studies have shown how predawn plant water potential (Ψpd) decreased during the growing season (Naor and Wample, 1994; Escalona *et al.*, 1999), especially from berry set to veraison, a time when a high vegetative expansion of vines is accompanied by berry growth (Escalona *et al.*, 1997). These studies agreed with our findings, while in other studies where vines were irrigated at 100%, ETc (crop evapotranspiration) showed Ψpd values fairly constant and around –0.4 MPa throughout the growing season (Schultz, 1996).

A decrease in Ψmd was also found along the season, and this fact was even found in other experiments where soil water content was maintained close to field capacity, perhaps because transpiration exceeded the capacity of the root system to supply water to the transpiring leaves (Matthews *et al.*, 1987). Our results indicated that the vines receiving the highest irrigation treatments can reach values that suggest severe water stress at midday.

Water stress decreased photosynthetic activity as also found by other authors (Poni *et al.*, 1994b; Araujo *et al.*, 1999; Flexas *et al.*, 1999) although it has been stated that, even in hard environmental conditions, vine leaves are capable of maintaining a certain degree of photosynthetic activity (Kliewer *et al.*, 1983; Escalona *et al.*, 1997). Taking into account that photosynthesis decreases when Ψ reaches –0.5 Mpa and ceases around –1.2 MPa (Hardie and Considine, 1976), the values we observed in predawn water potential in non-irrigated vines show that photosynthesis may be impaired in the hottest months.

The observed decrease in stomatal conductance during the studied period was very similar to that observed in net photosynthesis. There is general agreement that stomatal limitations account for most of the photosynthetic reduction observed in species well-adapted to drought, although it has also been reported that stomatal control of photosynthetic rate becomes progressively less effective as water stress intensifies (Escalona *et al.*, 1999). Stomata control is a major physiological factor in optimising the use of water (Giorio *et al.*, 1999). During periods of water stress, there is a reduction of gas exchange to prevent excessive water loss, which is why stomatal conductance was lower in non-irrigated vines and transpiration also decreased during the studied periods even when the evaporative demand increased as the season progressed, as we found in our studies.

Vegetative growth

Our results showed that shoot elongation is very sensitive to water. Some authors have shown that if water is not restricted, shoots of 250 cm could be obtained (Kliewer *et al.*, 1983; Matthews *et al.*, 1987), since irrigation increases the rate of shoot elongation during the phase of linear growth (Bravdo and Hepner, 1986). Kliewer *et al.* (1983) stated that reduction in the rate of shoot growth in irrigated and non irrigated vines can be detected even before any significant differences in predawn leaf water potential occurs, suggesting that the shoot growth rate is a very sensitive indicator of water stress.

Water stress also reduced leaf formation, phenomena attributed to the lower activity of the terminal meristem, a smaller leaf size and the senescence of basal leaves (Kliewer *et al.*, 1983). Our results showed that the reduction from June to September accounted for a 53, 30 and 50% in T1, T2 and NI vines respectively, showing that the decrease in T2 was the lowest.

Some studies have been made regarding the importance of principal and lateral leaves. Lateral shoots become net exporters of carbohydrates as soon as they have two fully expanded leaves. They provide assimilates to support their own growth and export the surplus to the main shoot, contributing to fruit ripening (Vasconcelos and Castagnoli, 2001). The most efficient leaves during ripening are located at the top of the canopy and those arising from lateral shoots (Candolfi-Vasconcelos and Klobet, 1994). In moderate vigour vineyards, lateral leaves improve fruit quality and are the most important contributors to both sugar accumulation in the fruit during ripening and to starch accumulation in the parent vine (Candolfi-Vasconcelos and Klobet, 1990). In June, leaves on lateral shoots did not present significant differences between vines with values ranging between 0.69 and 1.24 m^2 per vine.

Gómez del Campo *et al.* (2002) found that water stress produced a similar reduction in leaf area development in primary and lateral shoots, whereas Williams and Matthews (1990) stated that water stress reduced leaf area on lateral shoots to a greater extent than on primary shoots. Our findings did not agree with either of these statements since from June to September leaf area on the lateral shoots was only significantly reduced in T1 vines, whereas the decrease in NI vines was only 20% compared with a reduction of 65% in leaves in primary shoots and in T2 vines, the area in lateral shoots increased from June to September.

Productive parameters

It is accepted that one of the main results of irrigation is an increase in berry size and weight (Freeman and Kliewer, 1983; Matthews and Anderson, 1988; García-Escudero and Zaballa Ogueta, 1997), as we found in our results. Berry size may be important in determining the extraction and/or the dilution of the cell contents, which are clearly the primary site of several important solutes for winemaking.

The irrigated vines showed an evident increase in fertility. The negative effect of water stress on fertility, as expressed by fewer clusters per vine, fewer berries per cluster and a reduction in shoot growth, has been mentioned by other authors (Bravdo *et al.*, 1984) and is coincident with our results.

If NI and T2 vines are compared, water stress caused an average reduction in vine productivity of 74% in 2000 and 65% in 2001, although the decrease of net photosynthesis on the last sampling date was 52% and 45% in 2000 and 2001 for the same vines. Therefore, the reduction in vine productivity caused by water stress was due not only to lower net photosynthesis but also to other physiological changes in the vine such as perhaps the sensitivity of leaf area formation.

To characterise the supply/demand relationship of assimilates in the vine we can use the leaf area/fruit weight ratio (Bravdo and Hepner, 1986). Previous studies have reported that the amount of exposed leaf area to properly mature 1 g of fruit mass may vary from 7 to 17 $cm^2\ g^{-1}$ (Poni *et al.*, 1994a). We found a ratio of 10.5 in T1 and T2 treatments and 14.5 in NI vines, suggesting that in non irrigated vines production was low and uneconomic.

Another index that can be used to determine the equilibrium of the vegetative/reproductive growth is the Ravaz index. Jackson and Lombard (1993) stated that a value in the Ravaz index (kg of berries kg^{-1} of pruning weight) of between 4-8 reflects a high soluble solids content in the berries and a high polyphenol content. A value lower than 5 or higher than 10 can cause the opposite effect. T1 and T2 treatments showed values within this range. NI vines in 2001 did not reach the minimum value of 4.

As conclusions, this study has shown that in our climatic conditions non-irrigated vines suffer an important water deficit, as reflected by low predawn and midday water potentials. These low potentials, together with a significant stomatal closure to reduce water losses resulted in low values of net photosynthesis, with significant differences with irrigated treatments.

The water stress suffered by non-irrigated vines also affected leaf area, resulting in a very small canopy and very small pruning weight. Productivity was also affected. Non-irrigated vines showed the largest imbalance between productivity and vegetative growth. The results showed the importance that a moderate irrigation can have on Monastrell vines, ensuring a correct canopy development and a larger productivity. T2 vines showed the best vegetative and productive results without an excessive increase in berry size, a determining factor in wine quality grapes.

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