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ScienceDirect
Scientia Horticulturae 112 (2007) 321–330
SCIENTIA HORTICULTURAE
www.elsevier.com/locate/scihorti

Effects of deficit irrigation strategies on cluster microclimate for improving fruit composition of Moscatel field-grown grapevines

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Received 28 July 2006; received in revised form 29 December 2006; accepted 12 January 2007

Abstract

The grapevine plays a very important role in the economic, social and cultural sectors of many regions; however vineyards are often grown in regions under stressful conditions and thus they are vulnerable to climate change. The objective of this research was to investigate the effect of partial root-zone drying (PRD) irrigation on vine water relations, vegetative growth, plant microclimate, berry composition and yield components, compared to conventional deficit irrigation (DI, 50% ETc), full irrigation (FI, 100% of ETc) and non-irrigated vines (NI). The study was undertaken in mature 'Moscatel' grapevines (*Vitis vinifera* L.) grown in Pegões, South of Portugal. Compared to the other irrigated treatments, PRD vines showed a better microclimate at the cluster zone with higher incident photosynthetic photon flux density (PPFD). Within the more open canopies of NI and PRD treatments, berry temperatures were higher than those of denser ones (DI and FI). Compared to the conventional irrigation technique the better microclimate observed in PRD vines was a consequence of a reduction in vine growth, where lower values of leaf layer number, leaf area, canopy wideness, water shoots and shoot weight were observed. In PRD vines we observed a tendency to a development of a deeper root system, while DI and FI showed a more homogeneous root distribution throughout the different soil layers. PRD showed an improvement in berry quality with higher values of flavour precursors, and total phenols concentration without any significant yield reduction compared to DI and FI.

Keywords: Berry temperature; Canopy microclimate; Fruit quality; Partial rootzone drying; Roots; *Vitis vinifera* L.

1. Introduction

The Grapevines, namely for wine production is one of the most important crops within the Portuguese agriculture. Global environmental change with a predicted increase in aridity (Rizza et al., 2004), mainly in South Europe, will force modifications within the network of national and European regulations for grapevine/wine (Schultz, 2000; Chaves and Oliveira, 2004). These regulations aim at the optimization of wine quality for a given combination of geographical, soil, climate, cultivation and winemaking parameters. Due to climate change, there is a risk for a change in the quality of vine/wine, and consequently for its economic value. Although the impact of climate change is not likely to be uniform across all varieties and regions (Jones et al., 2005), a profound change in the distribution of suitable varieties within Europe may occur (Schultz, 2000).

Water resources in South of Portugal are limited leading to the re-evaluation of the current strategies of water use. Water is a renewable resource although it is distributed unevenly both geographically and time wise. Irrigation is a powerful management tool for improving vine performance provided it is properly managed. Irrigation management during the growing season is critical for control of vine vigour, berry size and berry quality. Excessive water induces a stimulus in vegetative growth that leads to denser canopies, and lower fruit exposure and, consequently, lower fruit quality and higher

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Abbreviations: DI, deficit irrigation; ETc, crop evapotranspiration; FI, full irrigation; G-G, glycosyl-glucose; IFT, total phenol index; LLN, leaf layer number; NI, non-irrigated; PRD, partial rootzone drying; PPFD, photosynthetic photon flux density; T_b, berry temperature

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doi:10.1016/j.scienta.2007.01.006

disease problems (Crippen and Morrison, 1986a,b; Dokoozlian and Kliewer, 1996; Keller and Hrazdina, 1998). Lateral shoot growth is particularly promoted, which will impose a competition for photosynthates and shading, creating conditions for an increase in berry and leaf diseases, and delaying berry maturation (Smart, 1994). On the contrary when water deficits occur, the vine responds by closing stomata to limit water loss. The different processes in the vine plant respond differently to water stress. Vegetative growth and early berry growth are very sensitive to water deficit while leaf photosynthetic function and post veraison berry growth are less sensitive processes (Shackel et al., 1987; Lu and Neumann, 1998). When drought increases stomata closes for longer periods of time, limiting photosynthesis and the production of sugar leading to poor fruit quality and reduced yield. An early stress will not allow an adequate shoot elongation and leaf development (Matthews et al., 1987). On the other hand, a severe water deficit after veraison can result in a high basal leaf senescence providing too much light at cluster zone (Kliewer et al., 1983; Smart and Robinson, 1991), with negative effects on berry quality. So, an optimal irrigation management will impose a plant water status that allows a good leaf physiological activity and at the same time reduces excessive shoot growth. Therefore a more open and balanced canopy will be achieved improving berry quality namely total phenols concentration (Smart et al., 1988; Keller and Hrazdina, 1998; Spayd et al., 2002).

Deficit irrigation strategies are relatively new tools for managing grapevine growth, improving fruit quality and water use efficiency, while maintaining yields. One of these strategies is the regulated deficit irrigation (RDI) which has been explored to control vegetative growth and improve fruit yield and quality (Goodwin and Jerie, 1992; McCarthy, 1997) by removing or reducing the irrigation input for specific periods during the growing cycle. According to Dry et al. (2001) RDI is used to manipulate winegrape quality by applying a short duration of water deficits immediately after berry set in order to control berry size and vegetative growth. A short period of water stress may also be imposed after veraison in order to enhance anthocyanin accumulation. Matthews et al. (1987) also observed that reduced irrigation prior to veraison caused a greater reduction in berry size than less irrigation after veraison did. This reduction in berry size is important because the flavour compounds which determine wine quality are mainly located in the berry skin and an increase in skin to flesh ratio might improve fruit quality (Dry et al., 2001). Although the higher skin to pulp ratio on smaller berries has been recently questioned by Roby and Matthews (2004) in Cabernet Sauvignon grapevines since a pre-veraison water stress reduces total berry weight but quite likely also hinders skin growth more than mesocarp growth and, consequently, smaller berries might have a similar lower skin to pulp ratio than bigger berries.

In drying soil, shoot growth can be limited as a result of hydraulic insufficiency, and of chemical signalling, involving transfer of chemical information from roots to the shoots via the xylem (Davies et al., 1994). Based on this fact a new irrigation technique called partial root-zone drying (PRD) has been studied by many authors (Dry and Loveys, 1998; Souza et al., 2003; Santos et al., 2005; Wakrim et al., 2005). It is an irrigation technique designed to keep part of the root-zone in drying soil and the rest of the root-zone well watered (Dry and Loveys, 1999; Stoll et al., 2000). The root-zones alternate every few weeks between dry and irrigated. It has been hypothesized that the water stress induced on one side of the root system will lead to the sending of signals to the shoots via the xylem (Dodd et al., 1996) stimulating the whole plant to utilize water more efficiently (Dry and Loveys, 1998). These signals (like ABA) lead to a partial stomatal closure and a reduction in shoot growth (Dry et al., 1996). So, PRD has the effect of controlling excessive vegetative growth in grapevines, leading to a reduction in canopy density and a better plant balance with decreased costs of maintenance (Dry et al., 2001; Santos et al., 2003). In addition, some studies had shown in PRD plants an increment increase in rooting depth (Dry et al., 2000) and root biomass (Mingo et al., 2004) compared to well-watered plants. At the end of other experiment unchanged shoot:root ratio was found in stressed vines receiving 100% of total plant transpiration in one pot with water withheld from the other, compared with control (Poni et al., 1992). This plant response may represent an increased ability to access soil resources, namely water and nutrients. Furthermore, several works on PRD showed that this irrigation method appears to provide benefits in fruit quality (Loveys et al., 2000; Santos et al., 2005).

Research studies found that grape glycosides act as flavour precursors having a high importance in wine aroma determination especially because most of varietals aromatic compounds in grape, musts and wines are present in bound-glycosylated forms (Sefton et al., 1993, 1994). The analysis of glycosylated secondary metabolites in grapes could give an objective measure of grape quality and be a useful parameter to allow the assessment of the effect of viticultural and winemaking practices (Williams et al., 1995). Although there are hundreds of glycosides present in grapes, with very different chemical structures, the determination of glycosyl-glucose (G-G) concentration gives the total concentration of glycosylated secondary metabolites (Francis et al., 1998), which are mainly related to aromatic compounds in the case of white grape varieties (Williams et al., 1995).

The aim of the present study was to provide a better understanding of the effect of different irrigation strategies, namely those where the same amount of water was applied, in the control of grapevine plant vigour, cluster microclimate and consequently berry quality and plant water-use efficiency.

2. Materials and methods

2.1. Field conditions and plant material

The field trial was carried out in 2002 at a commercial vineyard located at Pegões, Southern Portugal (70 km South of Lisbon). The climate is of the Mediterranean type, with hot and dry summers and mild winters, having an average annual rainfall of 550 mm, with 400 mm falling during the autumn and winter months. The soil is derived from podzols, mostly sandy and with a clay rich (low permeability) horizon at *ca.* 1 m depth. The 5-year-old vines of the white variety 'Moscatel de Setúbal' syn. 'Muscat of Alexandria' (*Vitis vinifera* L.), grafted on 1103 Paulsen rootstock, has a North–South row orientation. The vines were spaced 2.5 m between rows and 1.0 m along rows and trained on a vertical shoot positioning with two pairs of movable wires and spur pruned on bilateral Royat Cordon system at a height of 60 cm. The top of the canopy was approximately 1.40 m from the soil which gives a canopy height of 80 cm. All vines were uniformly pruned to 12 nodes per vine. Standard cultural practices in the region were applied to all treatments. Shoots were trimmed at about 30 cm above the higher movable wire, two times between bloom and veraison.

2.2. Irrigation and experimental design

Water was applied with drip irrigation method with two drippers per vine and with drip lines independently controlled and placed 30 cm from the vine trunk, out to both sides of the row. Watering was applied according to the crop evapotranspiration (ETc), estimated from the potential evapotranspiration (ETo), which was calculated from the Class A pan evaporation and using the crop coefficients (K_c) proposed by Prichard (1992). Each irrigated treatment was equipped with timing-valve assembly to control water delivery. The treatments were: full irrigated (FI, 100% of the ETc, half of water supplied to each side of the root system with 4 L h^{-1} drippers); deficit irrigated (DI, 50% of the ETc, half of water supplied to each side of the row with 2 L h^{-1} drippers); partial root drying (PRD, 50% of ETc periodically supplied to only one side of the root system with 4 L h^{-1} drippers) and non-irrigated (NI) treatment which was allowed to dry. The first change of the irrigation side was done after 1 month and then alternating sides every 15 days); non-irrigated (NI; rain fed). Watering was done twice a week, from fruit set (middle June) until 3 weeks before harvest which occurred on September 24. The total water amount supplied to FI plants was 196.8 mm (493 L $vine^{-1}$). The PRD and the DI vines received half of that quantity.

The experimental design was a Latin square with four treatments and four replications per treatment. Each replicate (plot) had three rows with 15–20 vines each and all the measurements were made on the central row.

2.3. Plant and soil water relations

Pre-dawn leaf water potential (Ψ_{pd}) was measured weekly from the beginning of berry development until harvest. Measurements were carried out on one adult leaf of six replicate plants from each treatment using a Scholander pressure chamber (Model 1000; PMS instrument Co., Corvallis, OR, USA). Leaves were enclosed in a plastic bag, immediately severed at the petiole and sealed into the humidified chamber for determination of the balancing pressure.

Soil water content was monitored twice a week (before and after each irrigation) during the growing season using a Diviner 2000^{TM} capacitance probe (Sentek Environmental Technologies, Stepney, Australia). Water content in the soil profile was determined using access tubes located 0.1 m from the row in four plants per treatment. Measurements were done each 0.1 m from soil surface to 0.9 m depth.

2.4. Root distribution

Roots were sampled after harvest using cylinders of soil (0.77×10^{-3} m^3), taken at four depths (m), 0.05–0.25, 0.25–0.45, 0.45–0.65, 0.65–0.85 and close to the drippers at two positions relative to the plant, on the right and left side in the row. For each treatment twelve plants were used. Each sample was stored in polyethylene bags and frozen until laboratory analysis. The roots were recovered by soil washing and root mass density (g m^{-3}) by depth calculated after the determination of root dry mass.

2.5. Canopy density and cluster microclimate

Canopy density was assessed by point quadrate analysis (Smart and Robinson, 1991), by inserting a needle at regular intervals into the fruit zone. Eighty horizontal insertions per treatment (20 per plot) were made using a pre-marked sampling guide.

Leaf area per shoot (8 shoots per treatment) was assessed periodically in count shoots from bud break onwards in a non-destructive way, using the methodologies proposed by Lopes and Pinto (2000). The area of single leaves was estimated using an empiric model based on the relationship between the length of the two main lateral leaf veins and leaf area measured with a leaf area meter (LI-3000; LI-COR Lincoln, Nebraska, USA). Leaf area per plant was calculated multiplying the leaf area per shoot by the shoot number.

Light at the cluster zone was measured on sunny days at midday using a Sunflek Ceptometer (model SF-40, Delta T Devices Ltd., Cambridge, UK) inserted horizontally at the cluster zone along the row. The values of incident photosynthetic photon flux density (PPFD) were expressed in percentage of a reference PPFD, measured over the canopy top. Berry temperature (T_b) was determined on clear sunny days using two representative exterior clusters per treatment of each canopy facing (east and west). Measurements were made continuously using fine-wired (36 American Wire Gauge [AWG]) two-junction thermocouples (type T [copper-constant]) which were manually inserted into the berries and connected to a data logger (Delta-T Devices Ltd., Cambridge, UK).

2.6. Yield, fruit quality and pruning weight

Berry ripening was followed from veraison until harvest. Sampling was done by collecting cluster fractions (3–4 berries per cluster) using a 200 berries sample per plot, collected in all vines and representative of all cluster positions within the canopy and of all positions within the cluster (Carboneau, 1991). Sub-samples per plot were used for fresh berry analysis for weight and volume, pH, soluble solids (Brix) using refractometry and titratable acidity by titration with NaOH as recommended by OIV (OIV, 1990). Another berry sub-sample

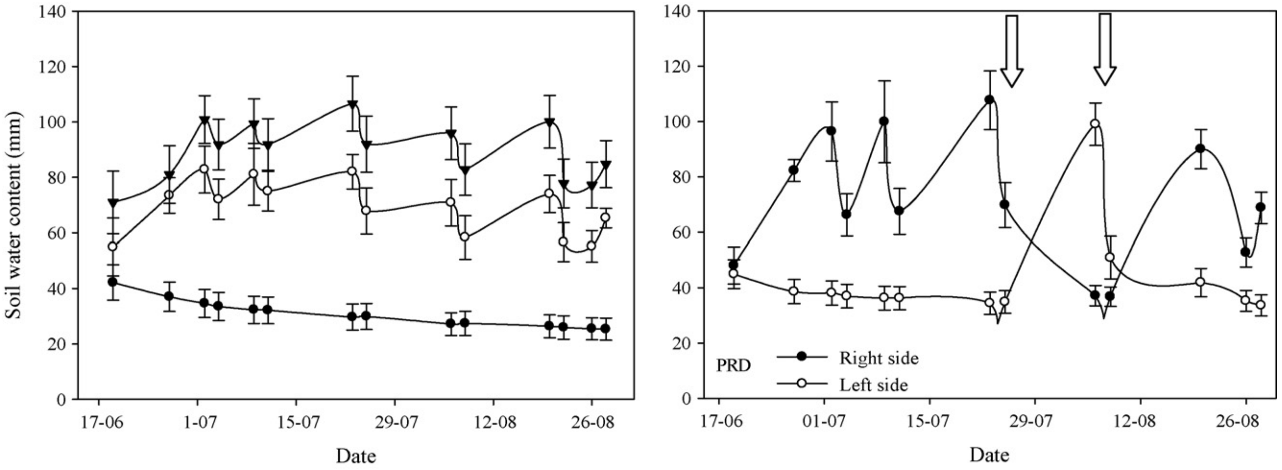

Fig. 1. The change of soil water content (0–0.9 m) during the 2002 growing season in Moscatel grapevines. Each arrow indicates the day when the change of rootzone-irrigated side took place in PRD treatment. Each point represents the average of four measurements with standard error.

per plot was frozen at −30 °C for later glycosyl-glucose and total phenolic compounds analysis. Total phenols were determined by spectrophotometry, by measuring Ultraviolet absorption at 280 nm (IFT) (OIV, 1990). Quantification of glycosides (glycosilated-volatile compounds or bound form of aromatic compounds) in grapes was obtained, measuring the glycosyl-glucose (G-G), according to Williams et al. (1995) and Iland et al. (1996). At harvest (September 24), yield components and fruit quality were assessed, following manual harvesting and weighting the production on-site. Cluster number and yield per vine were recorded for all vines on each plot. Irrigation water use efficiency (WUE) was estimated as the ratio of yield over the amount of applied water. At winter pruning, shoot number and pruning weight were also recorded and shoot weight was calculated.

2.7. Data analysis

Statistical data analysis was performed by analysis of variance (ANOVA). Tukey HSD tests were carried out to test the significance of differences between treatment means, using the STATISTICA software (ver. 5.0, Statsoft, Inc., Tulsa, OK, USA).

3. Results

3.1. Climate and soil–plant water relations

The growing season of 2002 was drier than the 30-year average, with the exception of March, with a total rainfall of 390 mm between January and September. Nevertheless, the air temperature followed the average pattern.

As shown in Fig. 1, the soil water content in the profile 0–0.9 m gradually decreased for NI plots from June to August. In the three irrigated treatments the soil water content was almost constant during June and July although a slight decline was observed in August resulting from the reduction in the irrigation amount. During the growing season, mean soil water content was in average three-folds in FI and two-folds in DI and PRD when compared to NI. In PRD the right side of the root-zone, the first one to be irrigated, had soil water content values almost 150% higher from those of the left side. The reverse occurred when the irrigation side was switched.

Pre-dawn leaf water potential (Ψ_{pd}) of FI vines remained constant and close to −0.2 MPa throughout the growing season, while in NI ones Ψ_{pd} decreased from June onwards, reaching mean values of −0.6 MPa at the end of August (Fig. 2). In PRD and DI plants, pre-dawn water potential decreased slightly from the beginning of the irrigation, with PRD showing a more favourable water status in some dates than DI.

3.2. Vegetative growth and root biomass

At veraison total leaf area per vine was significantly higher ($P < 0.05$) in FI than in NI and PRD treatments while DI plants showed values not significantly different from those of the other treatments (Table 1). These differences were mainly due to differences in the lateral shoot leaf area since main leaf area was similar in FI, DI and PRD and lowest in NI.

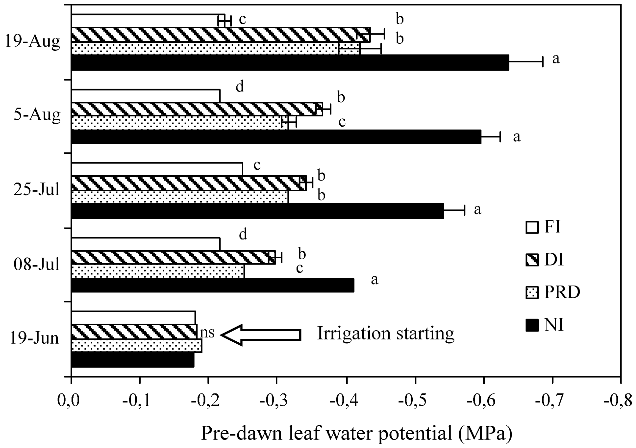

Fig. 2. Seasonal change of pre-dawn leaf water potential in Moscatel grapevines during the 2002-growing season. Each symbol represents the average of six measurements with standard error.

Table 1
Growth parameters measured at veraison or at pruning time (*) in Moscatel grapevines under four water treatments (NI, PRD, DI, FI) during the 2002 growing season

	NI	PRD	DI	FI	HSD	P
Shoot number/vine*	15.6	16.7	17.5	16.6	1.31	ns
Water shoots/vine*	1.5 c	2.0 b	3.0 a	3.0 a	0.59	≤ 0.001
Pruning weight (kg vine^{-1})*	0.45 c	0.48 bc	0.52 ab	0.54 a	0.59	≤ 0.001
Shoot weight (g)*	29.2 b	28.8 b	31.1 ab	33.4 a	4.23	≤ 0.001
Leaf layer number (no.)	1.9 d	2.4 c	3.5 b	4.0 a	0.43	≤ 0.001
Canopy wideness (cm)	45.4 c	45.0 c	57.1 b	64.8 a	3.04	≤ 0.001
Main leaf area (m^2 vine^{-1})	2.8 b	3.2 ab	4.0 ab	4.5 a	1.55	≤ 0.05
Lateral leaf area (m^2 vine^{-1})	1.9 b	1.7 b	2.1 ab	3.6 a	2.36	≤ 0.05
Total leaf area (m^2 vine^{-1})	4.7 b	4.9 b	6.0 ab	8.1 a	3.10	≤ 0.01

Columns of data within a row, followed with different letters (a–c), are significantly different at $P < 0.05$.

NI and PRD plants presented the narrowest canopies and FI the widest ones (Table 1) while DI showed an intermediate canopy wideness. Accordingly NI plants showed the lowest leaf layer number (LLN) while PRD showed a significantly lower LLN relative to FI and DI (Table 1).

While no significant differences were observed among treatments in the shoot number per vine, significant differences were registered in the number of water shoots (developed on the old woody stem), with NI showing the lowest value and PRD showing a significantly lower value than those of the other irrigated treatments. NI vines presented the lowest pruning weight per vine, which was significantly different from the FI and DI ones. PRD pruning weight was significantly lower than FI value, although not significantly different from DI (Table 1). Weight per shoot measured at winter pruning presented significantly lower values in PRD and NI relatively to FI, although no significant differences were observed between DI and the other three treatments.

In DI and FI no significant differences were found in the dry weight of roots between the different soil layers. On the contrary, in PRD plants a tendency was observed to the development of a deeper root system. Also, in NI plants the highest root dry weight occurred in the layer 0.45–0.65 m. Comparing the different soil layers between treatments we observed significant differences in the layer 0.05–0.25 m where NI presented a lower root dry weight compared to FI. In the layer 0.65–0.85 m PRD showed a significant higher root dry weight compared to NI (Fig. 3).

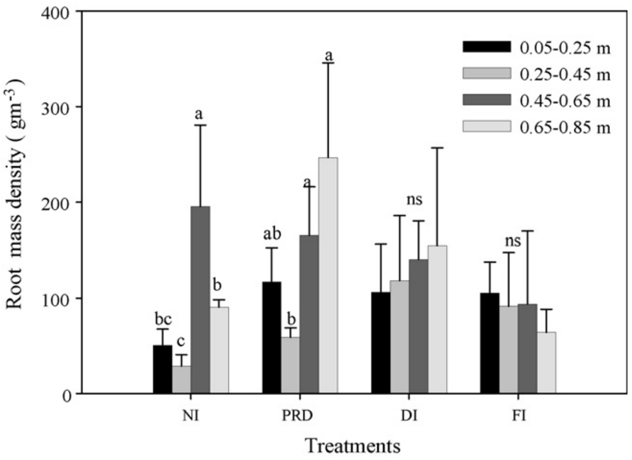

Fig. 3. Root dry weight in Moscatel grapevines under four water treatments (NI, PRD, DI, FI) in the 2002 growing season. Values shown represent the mean of 80 measurements with standard error. Different letters show statistically significant differences between different soil layers in each treatment at $P < 0.05$.

3.3. Canopy microclimate

FI vines had the highest LLN and, consequently, they displayed the lowest incident PPFD values during ripening at the cluster zone (Fig. 4). On the contrary, NI plants presented the highest cluster exposure. Within the irrigated treatments the reduction in vegetative growth observed in PRD resulted in a more open canopy as indicated by the significantly higher values of PPFD (10.2 ± 0.9%) received by the clusters when compared to DI (4.2 ± 0.5%) and FI (2.7 ± 0.3%).

The diurnal courses of berry temperature analysed at veraison for similar days of August (clear sky and high air temperature) on exterior clusters are shown in Fig. 5. In all treatments berry temperature (T_b) progressively increased from dawn, reaching maximum values about 11:00 h in the east canopy side and at 16:00 h in the west side. Berry temperatures were always higher in NI and PRD than in FI and DI vines, which presented denser canopies. The largest differences between air and berry temperature were reached at the east side around 11:00 h, the berries on NI presenting a temperature 5.5 °C higher than the air (T_a) as compared to 4 °C in FI, while in PRD and DI T_b exceeded T_a by 5.8 and 3.4 °C, respectively. During the night no differences between T_b and T_a were apparent except for DI and FI berries in the east canopy side which presented lower temperatures than the air.

3.4. Yield components and fruit composition

Cluster number per vine was independent of the soil water availability, although a significant increase in cluster weight was obtained as a result of irrigation with no differences between the irrigated treatments (Table 2).

When compared to NI, irrigation treatments had no significant effect on berry total soluble solids (Brix) and pH

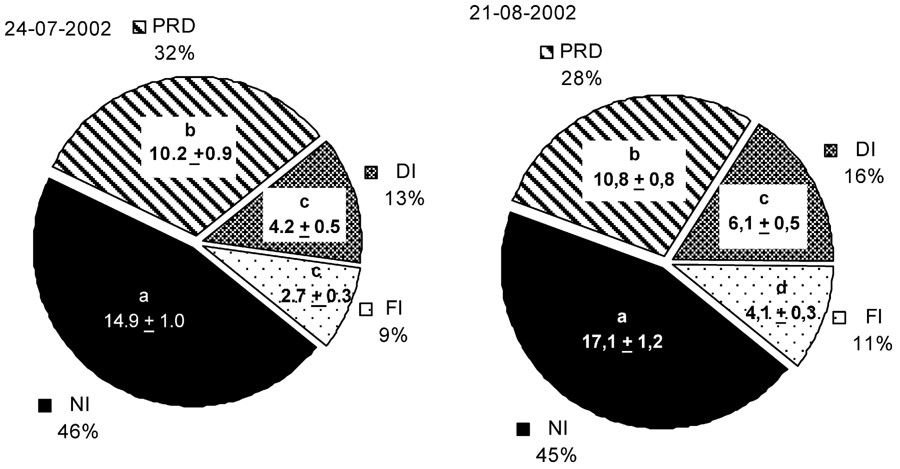

Fig. 4. Incident photosynthetic photon flux density at the cluster zone expressed as a % of a reference measured on top of the canopy in Moscatel grapevines under four water treatments during the 2002 growing season. Values shown represent the mean of 80 measurements with standard error. Different letters show statistically significant differences at $P < 0.05$.

(Table 2). Despite the absence of statistical significance PRD treatment displayed the highest total soluble solids value, when compared to NI, DI and FI. The titratable acidity was significantly higher in FI compared to NI and PRD while DI showed intermediate values. Among the irrigated treatments PRD presented the highest total phenols content which was similar to NI. Glycosyl-glucose (GG) was significantly higher in NI and PRD compared to FI and DI (Fig. 6). There was a significant increment in the total concentration of glycosylated secondary metabolites, like aromatic compounds, in PRD compared to the other irrigated treatments.

Irrigation water use efficiency (WUE, yield per unit of water applied) in PRD and DI treatments was the double of that observed in FI, which received the double amount of water.

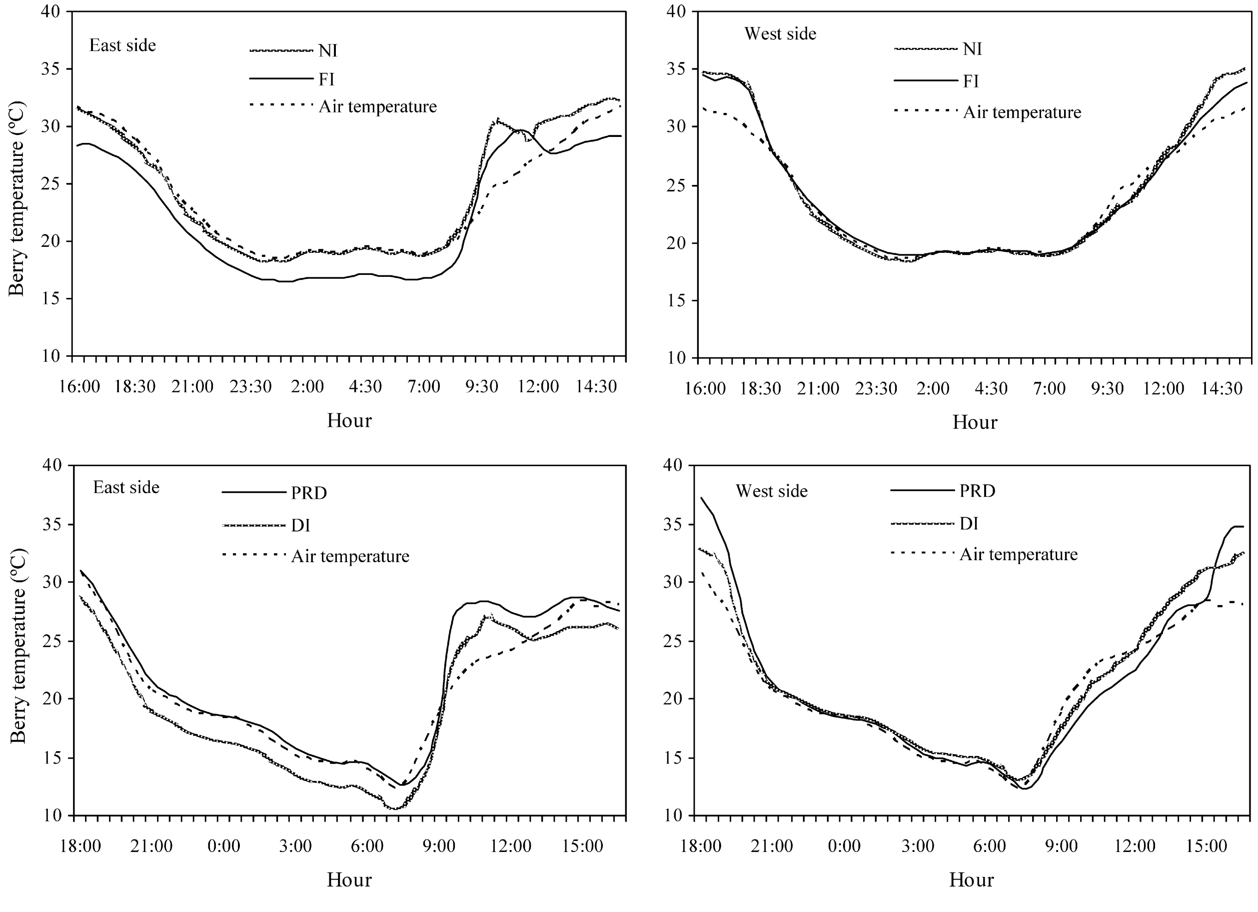

Fig. 5. Daily change of berry temperature at the cluster zone for exterior Moscatel grape clusters on the east and west sides of the canopy, during the 2002 growing season. FI and NI in east side; FI and NI in west side; PRD and DI in east side; PRD and DI in the west side.

Table 2
Yield components and berry composition at harvest in Moscatel grapevines under four water treatments (NI, PRD, DI, FI) during the 2002 growing season

	NI	PRD	DI	FI	HSD	*P*
Yield components						
Cluster number/vine	27.4	28.7	28.8	28.7	3.39	ns
Cluster weight (g)	377.5 b	407.0 a	398.0 a	395.3 a	1.48	$\leq$0.001
Yield/vine (kg)	9.18 b	11.45 a	11.53 a	11.45 a	1.48	$\leq$0.001
WUE (g_{berry} L^{-1})	na	46.6 a	46.8 a	23.3 b	4.75	$\leq$0.001
Berry composition						
Brix	15.8	17.0	15.9	15.6	3.28	ns
Phenols (IFT)	8.7 ab	8.7 a	8.0 bc	7.7 c	1.31	$\leq$0.05
Titratable acidity (g L^{-1})	3.4 b	3.4 b	3.5 ab	3.8 a	0.56	$\leq$0.05
pH	3.81	3.84	3.84	3.78	0.26	ns

Columns of data within a row, followed with different letters (a–c), are significantly different at $P < 0.05$.

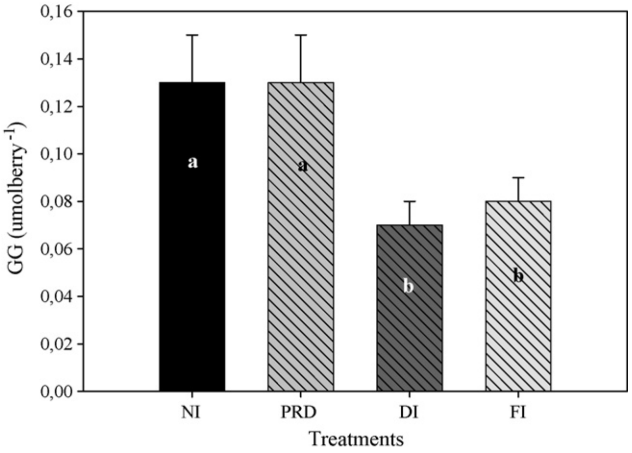

Fig. 6. Glycosyl-glucose in berries of Moscatel grapevines under four water treatments (NI, PRD, DI, FI) during the 2002 growing season. Values shown represent the mean of 4 measurements with standard error. Different letters show statistically significant differences at $P < 0.05$.

4. Discussion

The evolution of plant water status during the ripening period was in concert with changes of soil water content (Fig. 1). A mild water stress was experienced by DI and PRD plants which significantly decreased their plant water status comparatively to FI (Fig. 2), while NI plants gradually decreased their pre-dawn water potential to about −0.65 MPa, therefore exhibiting a more intense water deficit. Although the unwatered side of the root zone in PRD plants had a low water content (Fig. 1), available water on the wet side was sufficient to supply water to the aerial part, enabling a similar or even better plant water condition in PRD than in DI plants which, received the same amount of water. These results were consistent with those obtained in previous experiments in 2000 and 2001 with 'Castelão' and 'Moscatel' grapevines (Santos et al., 2003, 2005).

Water scarcity inhibits plant growth (Chaves et al., 2004) and in fact in the vines subjected to NI treatment a consistent reduction in vegetative growth was observed. Nevertheless, PRD had significant lower values of leaf layer number, percentage of water shoots and canopy wideness when compared to the other irrigated treatments, and lower values of shoot weight, pruning weight and total leaf area when compared with FI. This indicates a better control of vegetative growth, as also reported by Dry et al. (2001), Bravdo (2004) and Santos et al. (2005). FI vines during the growing season presented an high vegetative growth expressed by high values of LLN and leaf area, although during the winter until the pruning data, many of the lateral shoots and also part of the main shoots (beginning on the extremities) fell off, explaining the low values of pruning weight and shoot weight. So, we can say that Moscatel has a low potential shoot vigour (Dry and Loveys, 1998) but presents high vegetative growth during the growing season. The growth rate decline in PRD as compared to DI is apparently a response to signals received from the roots in the drying soil (Davies and Zang, 1991; Passioura, 1994), since both treatments received the same amount of water and PRD plants had similar or higher pre-dawn leaf water potentials. Dehydration of fine roots may promote the production of chemical signals which will restrict not only leaf conductance, but also plant growth (Loveys and Davies, 2004). Similar results to ours, pointing to a root-to-shoot signalling mechanism under PRD triggering vegetative growth were obtained in passion fruit by Turner et al. (1996). ABA seems to play a central role in the long distance drought signalling process (Davies and Zang, 1991; Loveys et al., 2000). In fact, many studies using split-root system found that when part of the root system experiences water deficit xylem ABA content increases. However, we did not observe any significant differences in ABA concentration transported in the xylem of PRD and DI plants (Rodrigues et al., unpublished). Nevertheless, some other chemical signals, such as cytokinins (Stoll et al., 2000; Davies et al., 2005) or alterations in ions content in the xylem sap (Wilkinson and Davies, 2002) may be involved in that regulation. A possible explanation for the lateral leaf area suppression and the lower canopy wideness in PRD compared to DI could be the reduction of cytokinins concentration since these hormones are known to be involved in the stimulation of growth of lateral shoots (Dry et al., 2001).

It is well known that drought may cause more inhibition of shoot growth than of root growth and in some cases the absolute root biomass in drying soil may increase when compared to the well watered soils (Sharp and Davies, 1989). The lower sensitivity of root growth to water stress appears to occur as a consequence of the rapid root osmotic adjustment in response to the decrease in soil water content, which allows the maintenance of water uptake and also due to the enhanced root cell wall loosening ability (Hsiao and Xu, 2000; Sharp et al., 2004). We observed in the soil profile an alteration in the root distribution in the plants with their root systems totally exposed (NI) or partially (PRD) to soil water depletion, expressed by the increased increment of the root biomass in the deeper soil layers. Conversely, FI and DI plants showed a homogeneous root mass density in the different layers of the soil profile. This contrasts with other studies where irrigation promoted shallow rooting systems (Proffitt et al., 1985; Carmi et al., 1992). However, our results in NI plants are in accordance to those obtained in other species, such as faba bean, where drought lead to an increased increment on rooting depth and root density (Husain et al., 1990) or maize where root dry biomass and length were increased under drying soil when compared to well-watered conditions (Schmidhalter et al., 1998). On the other hand, some studies using PRD in potted plants evidenced that development in both root length and dried mass was significantly enhanced in maize (Kang et al., 2002) and tomato (Mingo et al., 2004). Also Dry et al. (2000) observed in grapevines a significantly larger root area for ≥15 cm depth in 'dry' than in 'wet' containers.

Berry temperatures changed mostly in response to incident solar radiation being lower in the denser canopies of FI and DI than in the more open ones of NI and PRD. Higher berry temperatures were observed on the sun-exposed clusters of the west side of the canopy due to the normally higher ambient temperatures that occurred after noon (Spayd et al., 2002).

Exposure to sunlight influenced berry composition through temperature and incident radiation (Smart and Robinson, 1991; Dokoozlian and Kliewer, 1996; Bergqvist et al., 2001; Dokoozlian and Bergqvist, 2001). In our experiment the higher temperature and PPFD values observed in NI and PRD compared to FI and DI were positively correlated with the higher values of G-G and total phenols concentration, as also found by Spayd et al. (2002). Accordingly, Dry et al. (1996) and Loveys et al. (1998) had shown that the reduction in canopy density due to PRD enabled a better fruit quality expressed by higher concentrations of anthocyanins, phenols and glycosyl-glucose. Concerning the values of glycosylated aromatic precursors (G-G) that we obtained, they were consistent with those found in the literature for white grape varieties (Francis et al., 1998), although slightly lower, presumably as a result of the higher grape yields reached in this vintage (2002). The higher values of aromatic precursors obtained in PRD and NI berries, when compared to FI and DI ones may represent a quality improvement.

The higher concentrations of total phenols observed in NI and PRD can be explained by the better light microclimate at the cluster zone (17 and 10% of reference PAR, respectively) and also by the higher percentage of exposed clusters, as a result of the more open canopy. Additionally the higher concentration of total phenols in NI compared to FI may be explained by the lower berry weight observed in the NI treatment. It is generally assumed that smaller berries have a higher surface:volume ratio leading to a higher concentration of secondary metabolites in berry juice (Hardie et al., 1997). As we did not find significant differences in berry weight between DI and PRD grapevines the main reason for the differences in total phenols seems to be the indirect effect of the cluster microclimate (Williams and Matthews, 1990; Van Leeuwen and Seguin, 1994; Lopes et al., 2001; Santos et al., 2003, 2005) as a result of the lower canopy density obtained with PRD.

Cluster number per vine was independent of the water treatment, so the lower yields obtained in NI compared to the irrigated treatments were due to the lower cluster weight. The significant loss in weight of NI berries can be explained by the lower values of soil water content during all the growing season and the higher temperatures on berry cell elongation period, leading to a reduction in cell division in pericarp tissue (McCarthy, 1999) and to a shrinkage of berries during advanced stages of ripening (Crippen and Morrison, 1986a). NI vines presented the lowest yield value as compared to the irrigated treatments, although it corresponds to a high production (9 kg vine^{-1}). This can be explained by the fact that we are working with relative young vines and with a very productive clone. The major problem in the NI plants was the higher percentage of sunburned clusters, which compromised the yield for table grape.

As a consequence of the high fruit yield (7.4–9.0 kg vine^{-1}) and a relative low investment on vegetative growth, we obtained very high values in the yield to pruning weight ratio (21–24.3 kg/kg) and low values in the total leaf area to yield ratio (4.2–7.1 cm^2/g) suggesting that the vines were over-cropped (Bravdo et al., 1985). Indeed, total berry soluble solids did not reach the normal values for Moscatel variety at this region (about 22 Brix), confirming an over-cropping effect. However, the high rainfall values occurred in September (80 mm) before harvest also contribute to the low berry soluble solids values, leading to an important dilution of sugars and an increase in berry weight.

The effects of water availability on soluble sugar content are dependent on the cultivar. For example, Schultz (1996) reported a decrease in soluble sugar content for Grenache but not in Syrah for the same intensity of water stress. Irrigation did not significantly affect berry sugar accumulation confirming our previous studies (Santos et al., 2003, 2005). The higher titratable acidity observed in fully irrigated plants was consistent with results obtained in the 2000 and 2001 growing seasons (Santos et al., 2003, 2005). Indeed the increase of must titratable acidity is a common response to irrigation (Williams and Matthews, 1990) and may be beneficial for the wines of some varieties that have low acidity. In PRD and NI the lower titratable acidity was attributed to increased malic acid degradation due to the higher temperatures of exposed fruit (Kliewer, 1971). So a controlled water deficit may be an important tool to the musts deacidification in some varieties as defended by Matthews and Anderson (1988).

We can conclude that 50% of ETc (PRD and DI) is sufficient to guarantee all the 'Moscatel' yield potential since with half of the water applied in FI no significant yield reduction was observed leading to the double water use efficiency (amount of fruit produced per unit of water applied). Our results underline the interest of the PRD as a strategic irrigation management to reduce both water consumption and canopy density improving fruit quality as far as phenols and G-G, without affecting yield.

Acknowledgments

We thank to DRARO, namely to the Centro Experimental de Pegões for the experimental vineyard facilities and G. Rodrigues from I.S.A. for the technical assistance in measuring fruit composition parameters. This research was funded by the UE project IRRISPLIT (ICA – 1999 – 10026).

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