Vitis **44** (3), 117–125 (2005)

Effects of partial root-zone drying irrigation on cluster microclimate and fruit composition of field-grown Castelão grapevines

T. P. Santos[1)], C. M. Lopes[1)], M. L. Rodrigues[1)], C. R. de Souza[2)], J. M. Ricardo-da-Silva[1)], J. P. Maroco[2)], J. S. Pereira[1)] and M. M. Chaves[1),2)]

[1)] Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Lisboa, Portugal
[2)] Laboratório de Ecofisiologia Molecular, Instituto de Tecnologia Química e Biológica, Oeiras, Portugal

Summary

The partial root-zone drying (PRD) irrigation technique has been proposed for viticulture as a possible way to save water without compromising yield. Half of the plant root system is slowly dehydrating whereas the other half is irrigated; after about two weeks the opposite side of vines is irrigated. A PRD irrigation system (50 % of the crop evapotranspiration - ETc) was installed in a vineyard (*Vitis vinifera* L. cv. Castelão) in Southern Portugal and compared with two other irrigation systems, deficit irrigation, DI (50 % ETc) and full irrigation, FI (100 % ETc), as well as with non-irrigated vines (NI). Water was applied twice a week, from fruit set (mid-June) until one week before harvest (September 3). While FI vines remained well watered during the ripening period, a severe water stress developed in NI plants. PRD and DI vines exhibited mild water deficits during the same period. A significant decrease in vegetative growth (shoot weight, pruning weight, leaf layer number and percentage of water shoots) was observed in NI and PRD vines when compared to DI and FI. In denser canopies (FI and DI) berry temperature was always lower than that of the more open ones (NI and PRD). The higher degree of cluster exposition in PRD and NI had a positive influence on berry composition due to temperature and incident radiation, leading to higher concentrations of anthocyanins and total phenols in the berry skin compared to DI and FI vines. Irrigation did not significantly affect berry sugar accumulation and pH in berries. Compared to FI, PRD and DI treatments water use efficiency (the amount of fruit produced per unit of water applied) was doubled since at the same yield the amount of water applied, was reduced by 50 %.

K e y w o r d s : berry temperature, canopy microclimate, fruit quality, *Vitis vinifera* L., irrigation, partial rootzone drying, yield.

A b b r e v i a t i o n s : DI: deficit irrigation, ETc: crop evapotranspiration, ETo: potential evapotranspiration, FI: full irrigation, LLN: leaf layer number, NI: non irrigation, PRD: partial rootzone drying, PPFD: photosynthetic photon flux density, T_b: berry temperature, WUE, water use efficiency.

Introduction

For a long time, vineyard irrigation was uncommon in wine production in Portugal, because of possible negative effects on wine quality. Due to the severe water stress in the last decade irrigation became an increasingly common in central and southern parts of the country where high potential evaporation and low rainfall dominate during the growing season. It is now considered important for stabilizing yield and to warrant vine longevity.

Future climate scenarios suggest drier and warmer conditions for most of southern Europe, with longer dry summers and more severe plant water deficits (Schultz, 2000; Miranda *et al.* 2002). With enhanced pressure on water resources, the increasing demand for vineyard irrigation will only be met if there is an improvement in the efficiency of water use. This goal can be obtained by deficit drip-irrigation, including partial root-zone drying techniques (Loveys *et al.* 2000).

Regulated Deficit Irrigation (RDI) is one of the most frequently used drip-irrigation strategies in vineyards with the aim to balance grapevine vegetative and reproductive growth by applying less than the full vineyard water use at specific periods of the growing season (Chalmers *et al.* 1986; McCarthy 1997; Battilani 2000; Dry *et al.* 2001). One of the main objectives of RDI on red-wine cultivars is to reduce berry size, leading to an increase of the berry skin/flesh ratio and thus to an improvement of fruit quality. The management of RDI is, however, not easy. A major difficulty is the need for a reliable soil water monitoring system in order to avoid the risk of severe water stress in periods with extreme temperature events (Goodwin and Jerie 1992).

An irrigation technique called Partial Root-Zone Drying (PRD) was developed, allowing to control plant growth and transpiration avoiding severe water stress periods that can occur in RDI (Dry *et al*. 1996, Düring *et al*. 1997, Loveys *et al*. 2000). With the PRD technique part of the grapevine root system is slowly dried and while the remaining roots are exposed to wet soil. Thus, roots of the watered side maintain a favourable plant water status, while dehydrating roots will produce chemical signals that are transported to the shoots *via* the xylem and will hypothetically control vegetative vigour and stomatal aperture (Dodd *et al*. 1996; Dry *et al*. 1996). In recent years much information obtained under controlled conditions have provided evidence for a reduction of growth and gas exchange of plants in drying soil, without shoot water relations being affected (Davies *et al.* 1994; Liu *et al*. 2003).

There is an extensive experience with PRD irrigation of grapevines in Australia (Loveys and Davies 2004). In most cases, PRD resulted in a better control of vegetative growth,

Correspondence to: Dr. M. L. Rodrigues, Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal. E-mail: mlrodrigues@isa.utl.pt

providing an adequate exposure of clusters to sunlight and saving water without detrimental impacts on the quality and yield (Loveys *et al.* 2000). In addition to a favourable balance between vegetative and reproductive growth the lower vigour in PRD allows a more open canopy and, consequently, influences the light environment within the fruit zone. The beneficial effects on berry composition and metabolism are well documented, usually improving fruit colour and anthocyanin concentrations in red varieties in addition to a rise in total phenols (Crippen and Morrison 1986 a, b, Smart *et al.* 1988, Dokoozlian and Kliewer 1996, Keller and Hrazdina 1998, Spayd *et al.* 2002). An excessive cluster exposure may lead, however, to supra-optimal berry temperature with detrimental effects on grape berry composition. In fact, while in most wine-producing regions a high grape exposure is beneficial, in some warm regions the high temperature of fully exposed berries can reduce or even inhibit the synthesis of anthocyanins (Coombe 1992, Haselgrove *et al.* 2000, Bergqvist *et al.* 2001, Spayd *et al.* 2002).

The aim of the present study was to evaluate the response of Castelão grapevines to differences in soil water availability in the root system as a consequence of different irrigation techniques under field conditions. Two objectives were specifically addressed: (1) The effects of PRD on plant growth and canopy density. PRD plants were compared with vines that were rainfed (NI), fully irrigated (FI) or that received the same amount of water as PRD but distributed to both sides of the vines (DI). This treatment is important because earlier studies compared PRD with a system where the water given to each plant was twice as much as in PRD (Loveys *et al.* 2000). Field trials where PRD was compared with a control receiving the same amount of water are still scarce (Loveys *et al.* 2000, Santos *et al.* 2003); (2) the implications of the soil water regime on the cluster microclimate, in terms of radiation and temperature and on berry composition and quality.

Material and Methods

F i e l d c o n d i t i o n s a n d p l a n t m a t e r i a l: This study was carried out during the 2002 growing season in a commercial vineyard at the Centro Experimental de Pegões, southern Portugal (70 km south of Lisbon). The Mediterranean climate is hot and dry in summer and mild in winter, with an average annual rainfall of 550 mm, of which 400 mm are falling in autumn and winter. The soil is derived from a podzol, mostly sandy and with a clay-rich horizon (low permeability) at about 1 m depth. The experimental vines (*Vitis vinifera* L., cv. Castelão, a red wine variety) were 8 years-old and grafted on 1103 Paulsen rootstocks. The vineyard has a planting density of 4,000 vines per ha with vines spaced 1.0 m within and 2.5 m between rows. The spur-pruned vines were trained on a bilateral Royat Cordon system in north-south directed rows using vertical shoot positioning with two pairs of movable wires. All vines were pruned to 16 nodes per vine. The usual cultural practices of 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.

I r r i g a t i o n a n d e x p e r i m e n t a l d e s i g n: Irrigation was applied with drippers, two per vine, and independently controlled and positioned 30 cm from the vine trunk, at both sides of the row. Water was applied according to crop evapotranspiration (ETc), estimated from the potential evapotranspiration (ETo), which was calculated from Class A pan evaporation and using the crop coefficients (Kc) proposed by Prichard (1992). Each irrigation treatment was checked by a time clock-valve-assembly to control water supply. The treatments were: fully irrigated (FI, minimum water deficit, 100 % of the ETc, half of the water amount supplied by drippers, 4 $l \cdot h^{-1}$ to each side of the vine); deficit irrigated (DI, 50 % of the ETc, half of the amount of water supplied to each side of the row with 2 $l \cdot h^{-1}$ by drippers); partial root drying (PRD, 50 % of ETc periodically supplied to only one side of the vine by drippers, 4 $l \cdot h^{-1}$, while the other side tried); non-irrigated (NI, rainfed). In PRD the first change of the irrigation side of the vine was done after 1 month and then alternating sides every 15 d. Vines were watered twice a week, from fruit-set (mid-June) until one week before harvest (September 3). The total amount of water supplied to FI plants was 196.8 mm (493 l per vine). The PRD and the DI vines received half of this amount.

The experimental design was a Latin square with 4 treatments and 4 replications per treatment. Each replicate (plot) had 3 rows with 15 to 20 vines each and all the measurements were made in the central row.

P l a n t a n d s o i l w a t e r r e l a t i o n s: Pre-dawn leaf water potential (Y_{pd}) was measured weekly from the beginning of berry development (pea size) until harvest (second week of September). Measurements were carried out on one adult leaves of 6 replicate plants of each treatment and 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 moisture was monitored twice a week (before and after each irrigation) during the growing season until harvest using a Diviner 2000™ capacitance probe (Sentek Environmental Technologies, Stepney, Australia). Water content in the soil profile was determined down to 1.5 m depth all 0.1 m using access tubes located 0.1 m from the plant row.

C a n o p y d e n s i t y a n d c l u s t e r m i c r o c l i m a t e : Canopy density was assessed by point quadrat analysis (Smart and Robinson 1991). Eighty horizontal insertions per treatment (twenty per plot) were made at regular intervals into the fruit zone using a pre-marked sampling guide, enabling to calculate leaf layer number and the percentage of exposed clusters.

Leaf area per shoot (8 shoots per treatment) was assessed periodically in shoots from buds left at winter pruning (count shoots) after bud break in a non-destructive way (Lopes and Pinto 2000). Primary leaf area was estimated using a mathematical model with 4 variables: shoot length, leaf number and area of the largest and the smallest leaf. Lateral leaf area was estimated using a mathematical model with 4 variables: shoot length, leaf number and area of the largest and the smallest leaf. Lateral leaf area was estimated by a model that uses the same variables with the exception of lateral shoot length. 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 on 1,645 leaves of all sizes, using a leaf area meter (LI-3000; LI-COR Lincoln, Nebraska, USA). Leaf area per plant was calculated by multiplying the leaf area average by the mean shoot number.

Light at the cluster zone was measured on sunny days at midday using a Sunflek Ceptometer (model SF-40, Delta T Devices, Cambridge, UK) inserted horizontally at cluster zone along the row. The values of incident photosynthetic photon flux density (PPFD) were expressed in percentage of a reference PPFD, measured on top of the canopy. Berry temperature (T_b) was determined on clear, sunny days using two representative exterior clusters per treatment facing east and west. Measurements were made continuously using two-junction, fine-wires (36 American Wire Gauge [AWG]) thermocouples (type T, copper-constantan) wired in parallel, they were manually inserted about 3 mm into the berries and connected to a data logger (Delta-T Devices, Cambridge, UK).

Yield, fruit quality and pruning weight: The follow berry ripening samples of 200 berries per plot from all positions of the clusters (3-4 berries per cluster) were collected (Carbonneau 1991). Sub-samples were used for analysis of fresh weight, berry volume, pH, soluble solid (ºBrix by refractometry) and titratable acidity by titration with NaOH as recommended by OIV 1990). Another sub-sample of berries was frozen at -30 ºC for analyses of anthocyanins and total phenolics. Total phenols were determined by spectrophotometry measuring absorption at 280 nm (TPI, total phenols index, OIV 1990). Anthocyanins were measured by the sodium bisulphite discoloration method (Ribéreau-Gayon and Stonestreet 1965). At harvest, yield components and fruit quality were assessed after weighing clusters immediately after harvest. Number of clusters and yield per vine were recorded for all vines on each plot. Water use efficiency (WUE) of vines was estimated from the ratio between yield and the amount of supplied water. In winter, shoot number and pruning weight were also recorded and shoot weight and the ratio yield/pruning weight)was calculated.

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

Results

Climate and soil-plant water relations: In 2002 the growing season was drier than the 30-year-average with a total rainfall of 390 mm between January and September (exception: March, Fig. 1) while the air temperature followed the average pattern.

As shown in Fig. 2, for NI plots the soil moisture in the profile 0-0.9 m gradually decreases from June to August. In the three irrigated treatments soil moisture was almost constant during June and July although a slight decline was observed in August resulting from the reduction in the irrigation amount as a consequence of lower ETc values. During the growing season, mean soil moisture was in general 125 % higher in FI and 65 % in DI and PRD as compared to NI. In PRD the right side of the root-zone, which was irri-

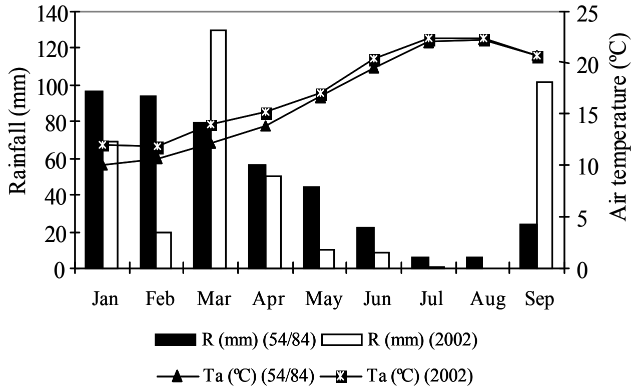

Fig. 1: Total rainfall (colums) and monthly mean air temperature (lines) at the experimental site during the 2002 season and average values (1954-1984).

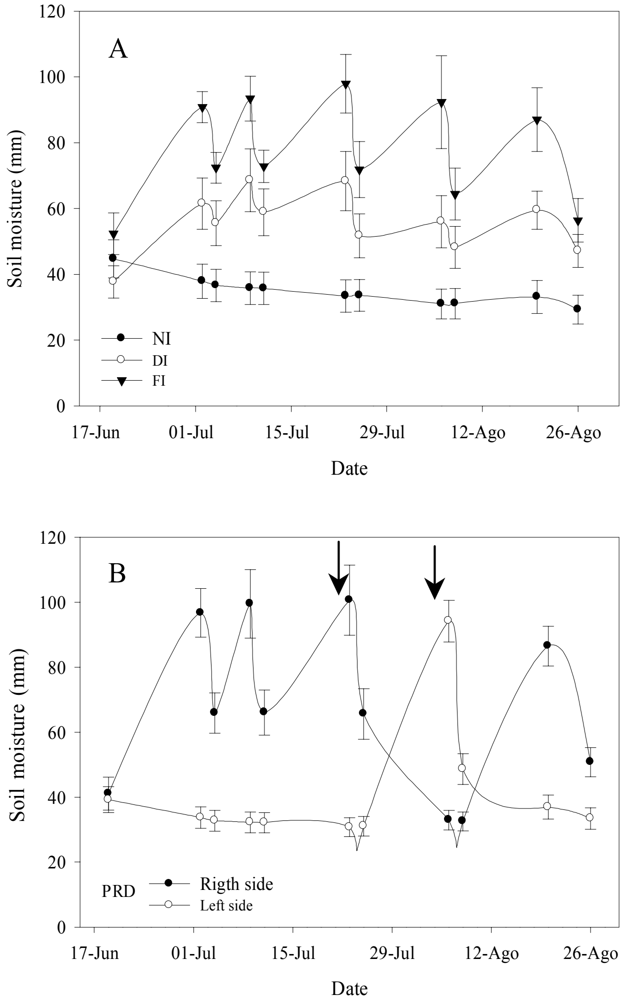

Fig. 2: Profile of soil moisture (0-0.9 m) of the experimental site measured *in situ* in the 2002 season. Arrows indicate changes of the side of irrigation in PRD treatment. **A**: ● - NI, ○- DI, ▼- FI, **B**: PRD treatment, ● - right and ○- left side of the root system. Each point represents the average of 4 measurements with standard error.

gated first, had soil moisture values almost twice those of the left side.

Pre-dawn leaf water potential (y_{pd}) of FI vines remained constant and close to -0.2 MPa throughout the growing season, while in NI y_{pd} decreased in June-July, reaching mean values of -0.8 MPa at the end of August (Fig. 3). Plant water potential of both PRD and DI plants decreased slightly from the beginning of irrigation, PRD having a higher water status (mean values of -0.35 MPa) than DI (mean values of -0.45 MPa). With exception of the last measurement, at end of August, y_{pd} of DI vines was significantly lower than that observed in PRD plants.

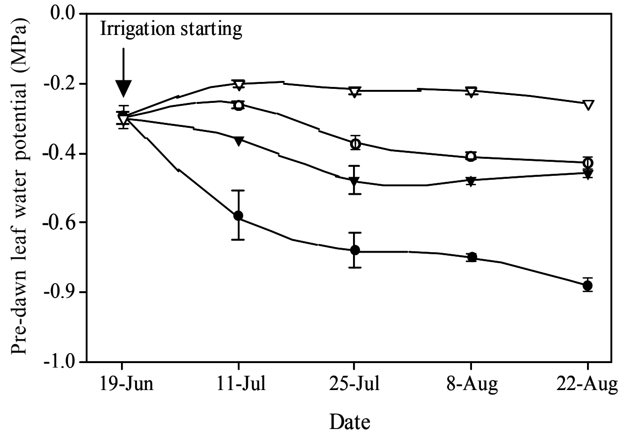

Fig. 3: Pre-dawn leaf water potential (● - NI, O- PRD, ▼- FI, ▽- FI). Each symbol represents the average of 6 measurements with standard error.

V e g e t a t i v e g r o w t h a n d c a n o p y m i c r o c l i m a t e : Shoot weight (measured in winter) was significantly lower in PRD and NI compared to FI and DI, although no significant differences in the shoot number per vine were observed among treatments (Tab. 1). Similar differences were observed in the number of water shoots (developed at the trunk), with NI and PRD showing values significantly lower than those of the other irrigated treatments. NI and PRD vines had the lowest pruning weight per vine; these values were significantly different from those of FI and DI ones (Tab. 1).

At veraison total leaf area per vine was significantly higher (P <0.05) in FI than in NI and PRD vines; values of DI vines were not significantly different from those of FI and PRD (Tab. 1). The differences of total leaf area between treatments were mainly due to differences in the lateral shoot leaf area; primary shoot leaf area was similar in the different treatments.

During ripening, NI plants showed the lowest leaf layer number. PRD canopies had a significantly lower leaf layer number (LLN) relative to FI and DI (Fig. 4). During August DI presented values between PRD and FI. FI vines had the highest values of LLN and displayed the lowest incident PPFD values at the cluster zone (Fig. 5). The reduction in vegetative growth observed in PRD resulted in a more open canopy as indicated by the significant increase of PPFD at the clusters when compared to DI and FI. A high and significant coefficient to determination was obtained when LLN was plotted against PPFD at the cluster zone, when data of all treatments throughout the growing season were considered (Fig. 6).

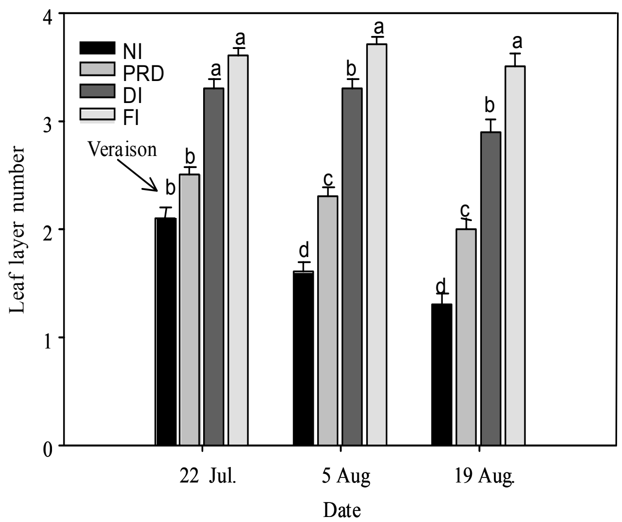

Fig. 4: Leaf layer number measured between veraison (end of July and mid-August). Values represent means of 80 measurements with standard error. Different letters show statistically significant differences at P < 0.05.

T a b l e 1

Growth parameters at veraison (leaf area) or at pruning time of the 4 water treatments (NI, PRD, DI, NI). Different letters show statistically significant differences among treatments at P<0.05

	NI	PRD	DI	FI
Shoot number per vine	19.4 a	19.0 a	21.0 a	19.8 a
Weight per shoot (g)	47.9 b	56.1 b	76.2 a	74.9 a
Water shoots per vine	2.7 b	2.9 b	5.5 a	4.7 a
Pruning weight (kg per vine)	0.9 b	1.1 b	1.5 a	1.5 a
Main leaf area (m^2 per vine)	4.4 a	4.6 a	5.5 a	6.2 a
Lateral leaf area (m^2 per vine)	0.8 b	1.0 ab	1.5 a	1.5 a
Total leaf area (m^2 per vine)	5.2 c	5.6 bc	7.0 ab	7.7 a
Crop load (yield per pruning weight)	5.0	5.6	4.2	4.2

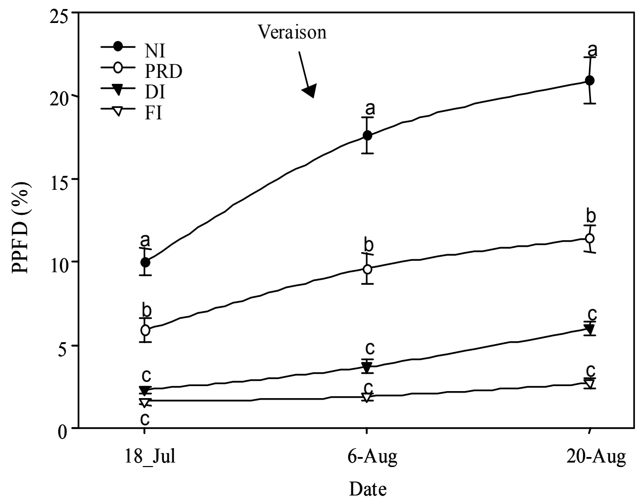

Fig. 5: Incident photosynthetic photon flux density at the cluster zone during the 2002 growing season. Values represent means of 80 measurements with standard error.

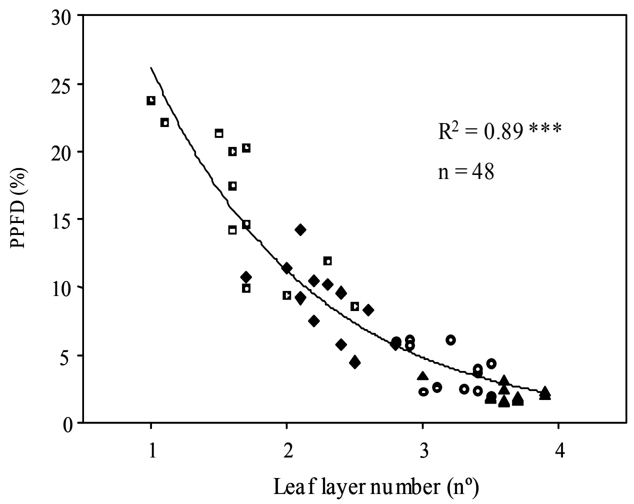

Fig. 6: Relationship between leaf layer number and photon flux density at the cluster zone for 4 water treatments (■- NI, ◆- PRD, ●- DI, ▲- FI, *** - significant at $\alpha = 0.001$.

Diurnal courses of berry temperature analysed at veraison (in August) with clear sky and high air temperature are shown in Fig. 7. For all treatments and at both canopy sides berry temperature progressively increased after dawn, reaching maximum values at about 16:00 h. Increases in berry temperature (T_b) due to sunlight was more obvious in NI and PRD than in FI and DI vines, due to their denser canopies. Higher berry temperatures were observed in NI and PRD vines, 36.6 ºC and 37.7 ºC respectively. The largest differences of T_b between NI and FI plants were reached at the east side of exterior clusters by about 10:00 h (4 ºC), while at the west side it occurred in the afternoon (3 ºC). A similar diurnal evolution of T_b was lower during the day. However, the differences were smaller than those registered when comparing NI to FI vines. During the night T_b was not different between the treatments.

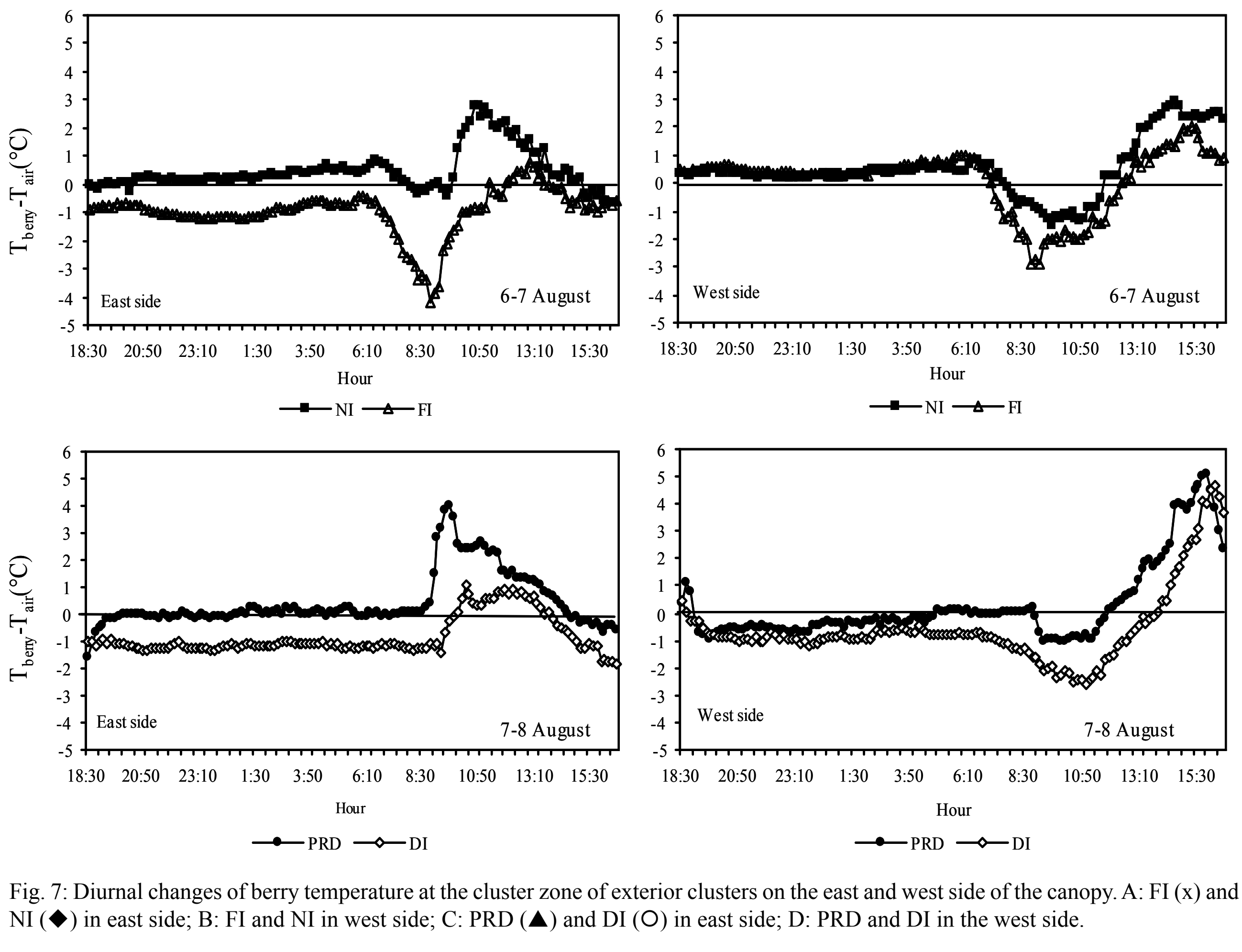

Fig. 7: Diurnal changes of berry temperature at the cluster zone of exterior clusters on the east and west side of the canopy. A: FI (x) and NI (◆) in east side; B: FI and NI in west side; C: PRD (▲) and DI (O) in east side; D: PRD and DI in the west side.

Y i e l d c o m p o n e n t s a n d f r u i t c o m p o s i t i o n : Berry weight and volume increased significantly as a result of irrigation (Fig. 8). From berry set to veraison (July, 25), a rapid increase in berry weight and volume was observed for all treatments, differences being more apparent between irrigated and NI vines. During ripening the increase in berry weight was greater for the FI treatment followed by DI and PRD. At harvest, NI vines presented the significantly lowest berry weight while the three irrigated treatments showed similar values.

In the first two weeks after veraison rates of skin anthocyanin accumulation were high, they declined thereafter until harvest (Fig. 8). No differences between treatments were observed at veraison; thereafter NI and PRD grapevines showed higher values than DI and FI. Total phenols decreased for all treatments from pea berry size to veraison and then increased distinctly two weeks before harvest. During ripening PRD had the highest total phenol values while values for FI were lowest.

At harvest berry composition differed with irrigation treatments. When compared to NI, irrigation had no significant effect on berry total soluble solids (ºBrix) and pH but led to a significant increase in the must titratable acidity of FI (Tab. 2). The lowest values for titratable acidity (3.9 g·l^{-1}), however, were obtained in the NI and PRD treatments. Among the irrigated treatments PRD presented the highest anthocyanin concentration, which differed significantly from DI and FI. Similarly, PRD showed significantly higher values of total phenols as compared to the other treatments which had similar values. The cluster number per vine was not affected by soil water availability, an important reduction in cluster weight was obtained in NI resulting in a significant yield decrease (Tab. 3). Water use efficiency (WUE, yield per unit water applied) in PRD and DI treatments was almost twice that observed in FI, which had received the double amount of water.

Discussion

The severity of water stress sustained during the ripening was roughly proportional to the amount of water supplied. These results, namely the seasonal pattern of predawn leaf water potential, were consistent with similar experiments in 2000 and 2001 (Santos *et al.* 2003). Nevertheless, although PRD and DI plants had obtained the same amount of water, y_{pd} was consistently higher in PRD than in DI.

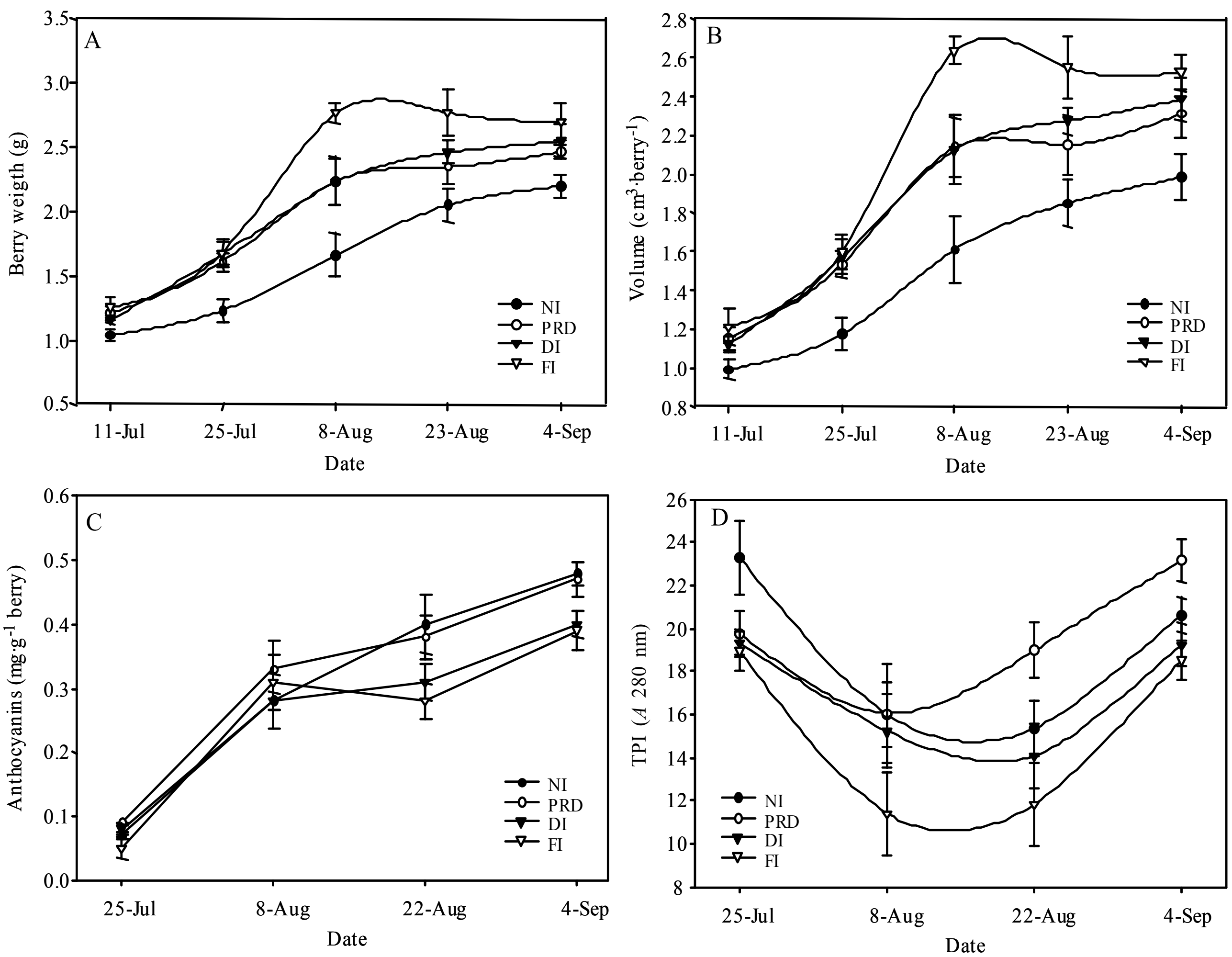

Fig. 8: Berry fresh weight (**A**), berry volume (**B**), anthocyanin concentration (**C**) and total phenol index, TPI (**D**) during ripening. Values are means of 4 samples with standard error.

Table 2

Berry composition at harvest. For details see Tab. 1

Berry composition	NI	PRD	DI	FI
Brix	19.0 a	19.7 a	18.7 a	18.9 a
Anthocyanins ($mg \cdot l^{-1}$)	799.1 a	820.6 a	682.2 b	646.4 b
Total phenols index (TPI)	20.6 b	23.2 a	19.2 b	18.9 b
Titratable acidity ($g \cdot l^{-1}$)	3.9 b	3.9 b	4.3 ab	4.8 a
pH	3.92 a	3.88 a	3.81 a	3.82 a

Table 3

Yield components and water use efficiency. For details see Tab. 1

Yield components	NI	PRD	DI	FI
Mean cluster number/vine	21.7 a	23.9 a	23.1 a	24.9 a
Mean cluster weight (g)	188.0 b	260.8 a	275.9 a	254.2 a
Yield ($t \cdot ha^{-1}$)	16.1 b	24.6 a	25.3 a	25.4 a
WUE (g berry$\cdot l^{-1}$)	na	24.9 a	25.7 a	12.9 b

PRD included a significantly lower leaf layer number, percentage of water shoots, shoot weight and pruning weight when compared with the other irrigated treatments; this confirms a better control of vegetative growth, as reported by Loveys *et al.* (2000) and Dry *et al.* (2001). The higher growth restriction in PRD as compared to DI suggests that a chemical regulation is superimposed on hydraulic signalling, because in both treatments the same amount of water was applied and PRD had higher water potential. This means a close link of shoot physiology to soil water distribution in the root-zone, pointing to the importance of the root-to-shoot signalling (Loveys and Davies 2004). Dry *et al.* (2001) also observed shoot growth inhibition in PRD vines in parallel with a marked decrease in the concentration of cytokinins in shoots and roots. This effect was reversed by the exogenous application of a synthetic cytokinin. A marked reduction in leaf area without a change in the leaf water status was also observed in split-root experiments with other woody species, such as apple (Gowing *et al*. 1990) and passion fruit (Turner *et al.* 1996), although these trials were not performed under field conditions.

Berry temperature were always lower in the dense canopies of FI and DI than in the more open canopies of NI and PRD. On the other hand, berry temperatures of sun-exposed clusters were higher at the west-facing canopy compared to the east-facing canopy due to the high ambient temperature in the afternoon. Similar results were reported for cv. Merlot (Spayd *et al*. 2002). Under the conditions of our experiment the higher cluster exposure to sunlight in PRD and NI influenced berry composition positively, confirming studies of Bergqvist *et al.* (2001), Smart and Robinson (1991) and Dokoozlian and Kliewer (1996).

The changes in the concentration of anthocyanins and total phenols in the berries during ripening and the effect of irrigation are in accordance with data in literature (Jordão *et al.* 1998). Exposure to sunlight influenced berry composition, suggesting that anthocyanin metabolism responds to both light and temperature (Smart *et al.* 1988; Haselgrove *et al.* 2000). In our experiments the higher temperature and incident light values measured during ripening in NI and PRD compared to FI and DI were associated with higher concentrations of anthocyanins and total phenols, as found by Spayd *et al.* (2002). In contrast, Keller and Hrazdina (1998) showed that for Cabernet Sauvignon, the anthocyanin concentration in berries was similar at 20 % and 100 % sunlight interception. It appears that if light conditions within a canopy are above a given threshold light is not necessarily a limiting factor for the synthesis of anthocyanins. So we conclude that under our conditions high temperature was not a limiting factor although it was shown to negatively affect fruit quality by inhibiting anthocyanin synthesis or increasing anthocyanin degradation (Kliewer and Torres 1972; Haselgrove *et al*. 2000). If clusters are severely shaded, as in FI plants, it is likely that light is a limiting factor for anthocyanin synthesis during berry ripening.

The main reason for the higher concentrations of total anthocyanins and total phenols in NI and PRD appears to be higher percentage of sunlight-exposed clusters, as a result of the reduction in canopy density. In climates where temperatures regularly exceed 30 ºC during ripening, moderately open canopies like those obtained in PRD vines appear to create optimal conditions for anthocyanins and total phenol synthesis. Similar results were obtained by Haselgrove *et al.* (2000) in their trials with Syrah vines in South Australia.

An additional factor for the significantly lower concentrations of anthocyanins and total phenols in FI and DI can be the higher rates of berry growth decreasing the skin to flesh ratio. Since, however, differences in berry volume between DI and PRD grapevines were not significant we assume that the main reason for differences is the indirect effect of the cluster microclimate (Nadal and Arola 1987, Williams and Matthews 1990, Van Leeuwen and Seguin 1994, Lopes *et al.* 2001).

The yield differences among treatments were mainly due to cluster weight since cluster number was not significantly different. The lower soil water content in NI vines and the effects of elevated berry temperatures on berry cell elongation, as well as increased cluster transpiration rates and subsequent berry dehydration (Crippen and Morrison 1986 a) are the main reasons to explain the berry weight decrease in NI vines. No significant differences in yield were observed between the irrigation treatments even though FI received twice as much water as PRD or DI. This indicates that berry growth was not affected by the mild water stress under PRD and DI conditions. This may be explained by the fact that mild stress occurred during ripening, when berry size is less sensitive to water stress (Williams and Matthews 1990). Even with higher yields, irrigated vines were able to maintain the ratio yield/pruning weight within the range considered by Smart and Robinson (1991) for a balanced vine.

Irrigation did not significantly affect berry sugar accumulation. These results are in contrast with those obtained by other authors who observed either an increase (Schultz 1996, Lopes *et al.* 2001) or a decrease (Jordão *et al.* 1998, Pire and Ojeda 1999) of berry sugar content at high soil water availability. It appears that in our experiment berries were active sinks for carbohydrates under the moderate drought stress (DI and PRD) and even under severe water stress (NI). The response of must titratable acidity to irrigation was consistent with results obtained in the 2000 and 2001 growing-seasons (Santos *et al.* 2003). The increase of must titratable acidity in fully irrigated plants is a common response to irrigation (Williams and Matthews 1990) and is considered beneficial for wines produced in hot areas, as they usually present a low acidity.

As a result of the 50 % reduction in the amount of water applied without any significant yield reduction, water use efficiency was double in PRD and DI treatments when compared to FI. These results, combined with the higher fruit quality in PRD vines, due to the higher concentration of anthocyanins and total phenols underline the strong interest in this irrigation strategy.

Acknowledgments

We are grateful to DRARO, namely to the Centro Experimental de Pegões for the experimental vineyard facilities, E. Oreca and D. Campilho for their help on data collection and G. Rodrigues for the technical assistance in measuring fruit composition parameters. This research was funded by the UE project IRRISPLIT (ICA-1999-10026).

References

Battilani, A.; 2000: Application of the regulated deficit of irrigation to grapevines (*Vitis vinifera*) in a sub-humid area. Acta Hortic. **537**, 887-893.

Bergqvist, J.; Dokoozlian, N.; Ebisuda, N.; 2001: Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in the Central San Joaquin Valley of California. Am. J. Enol. Vitic. **52**, 1-7.

Carbonneau, A.; 1991: Observation sur vigne: Codification des donnés agronomiques. Riv. Vitic. Enol. **4**, 37-45.

Chalmers, D. J.; Burge, G.; Jerie, P. H.; Mitchell, P. D.; 1986: The mechanism of regulation of 'Bartlett' pear fruit and vegetative growth by irrigation withholding and regulated deficit irrigation. J. Am. Soc. Hortic. Sci. **111**, 904-907.

Coombe, B. G.; 1992: Research on development and ripening of the grape berry. Am. J. Enol. Vitic. **43**, 101-110.

Crippen, D. D.; Morrison, J. C.; 1986 a: The effects of sun exposure on the compositional development of Cabernet Sauvignon berries. Am. J. Enol. Vitic. **37**, 235-242.

Crippen, D. D.; Morrison, J. C.; 1986 b: The effects of sun exposure on the phenolic content of Cabernet Sauvignon berries during development. Am. J. Enol. Vitic. **37**, 243-247.

Davies, W. J.; Tardieu, F.; Trejo, C. L.; 1994: How do chemical signals work in plants that grow in drying soil? Plant Physiol. **104**, 309-314.

Dodd, I. C.; Stikic, R.; Davies, W. J.; 1996: Chemical regulation of gas exchange and growth of plants in drying soil in the field. J. Exp. Bot. **47**, 475-1490.

Dokoozlian, N. K.; Kliewer, W. M.; 1996: Influence of light on grape berry growth and composition varies during fruit development. J. Am. Soc. Hortic. Sci. **121**, 869-874.

Dry, P. R.; Loveys, B. R.; Botting, D.; During, H.; 1996: Effects of partial root-zone drying on grapevine vigour, yield, composition of fruit and use of water, 126-131. Proc. 9th Aust. Wine Indust. Tech. Conf., Australia.

Dry, P. R.; Loveys, B. R.; McCarthy, M. G.; Stoll, M.; 2001: Strategic irrigation management in Australian vineyards. J. Int. Sci. Vigne Vin **35**, 129-139.

Düring, H.; Loveys, B. R.; Dry, P. R.; 1997: Root signals affect water use efficiency and shoot growth. Acta Hortic. **427**, 1-14.

Goodwin, I.; Jerie, P.; 1992: Regulated deficit irrigation: from concept to practice. Advances in vineyard irrigation. Aust. New Zealand Wine Indust. J. **7**, 258-261.

Gowing, D. J. G.; Davies, W. J.; Jones, H. G.; 1990: A positive root-sourced signal as an indicator of soil drying in apple, *Malus x domestica* Borkh. J. Exp. Bot. **41**, 1535-1540.

Haselgrove, L.; Botting, D.; van Heeswijck, Hoj, P. B.; Dry, P. R.; Ford, C.; Iland, P. G.; 2000: Canopy microclimate and berry composition: The effect of bunch exposure on the phenolic composition of *Vitis vinifera* L. cv. Shiraz grape berries. Aust. J. Grape Wine Res. **6**, 141-149.

Jordão, A. M.; Ricardo-da-Silva, J. M.; Laureano, O.; 1998: Influence of irrigation on phenolic composition of Touriga Francesa (*Vitis vinifera* L.). Ciencia Tecnol. Alimentos **2**, 60-73.

Keller, M.; Hrazdina, G.; 1998: Interaction of nitrogen availability during bloom and light intensity during veraison. II. Effects on anthocyanin and phenolic development during grape ripening. Am. J. Enol. Vitic. **49**, 341-349.

Kliewer, W. M.; Torres, R. E.; 1972: Effect of controlled day and night temperatures on grape coloration. Am. J. Enol. Vitic. **23**, 71-77.

Leeuwen van, C.; Seguin, G.; 1994: Incidences de l'alimentation en eau de la vigne appreciée par l'etat hydrique du feuillage, sur le developpment de l'appareil végétatif et la maturation du raisin (*Vitis vinifera* variéte Cabernet franc, Saint-Emilion 1990). J. Int. Sci. Vigne Vin **28**, 81-110.

Liu, F. L.; Jensen, C. R.; Andersen, M. N.; 2003: Hydraulic and chemical signals in the control of leaf expansion and stomatal conductance in soybean exposed to drought stress. Funct. Plant Biol. **30**, 65-73.

Lopes, C.; Vicente-Paulo, J.; dos Santos, T.; Rodrigues, M. L.; Barroso, J.; Chaves, M. M.; 2001: An Attempt to Quantify Grapevine Water Stress in a Mediterranean Environment, vol. 1, 43-48. Proc. XIIémes Journées GESCO, AGRO, Montpellier, France.

Lopes, C.; Pinto, P. A.; 2000: Estimation de la surface foliaire principale et secondaire d'un sarment de vigne. Progr. Agric. Vitic. **117**, 160-166.

Loveys, B. R.; Davies, W. J.; 2004: Physiological approaches to enhance water use efficiency in agriculture: exploiting plant signalling in novel irrigation practice. In: M. Bacon (Ed.): Water Use Efficiency in Plant Biology, 113-141. Blackwell Publishing, Blackwell.

Loveys, B. R.; Dry, P. R.; Stoll, M.; McCarthy, M. G.; 2000: Using plant physiology to improve the water efficiency of horticultural crops. Acta Hortic. **537**, 187-197.

McCarthy, M. G.; 1997: The effect of transient water deficit on berry development of Shiraz *Vitis vinifera* L. Aust. J. Grape Wine Res. **3**, 102-108.

Miranda, P.; Coelho, F. E. S.; Tomé, A. R.; Valente, M. A.; 2002: 20th Century Portuguese Climate and Climate Scenarios. In: F. D. Santos, K. Forbes, R. Moita (Eds): Climate Change in Portugal. Scenarios, Impacts, and Adaptation Measures, 25-83. Lisboa, Portugal.

Nadal, M.; Arola, L.; 1987: Effects of limited irrigation on the composition of must and wine of Cabernet Sauvignon under semiarid conditions. Vitis **26**, 147-160.

OIV; 1990: Recueil des Méthodes Internationales d'Analyses des Vins et des Moûts. Bull. O I V (Off. Int. Vigne Vin), Paris.

Pire, R.; Ojeda, M.; 1999: Vegetative growth and quality of grapevine 'Chenin blanc' irrigated under three pan evaporation coefficients. Fruits **54**, 135-139.

Prichard, T. L.; 1992: A Volume Balance Approach to Quality Wine Grape Irrigation. In: M. A. Walker, W. M. Kliewer (Eds): Viticultural Practices, 12-23. Univ. California, Davies.

Ribéreau-Gayon, J.; Stonestreet, E.; 1965: Le dosage des anthocyanes dans le vin rouge. Bull. Soc. Chim. **9**, 2649-2652.

Santos, T. P.; Lopes, C. M.; Rodrigues, M. L.; Souza C. R.; Maroco, J. P.; Pereira, J. S.; Silva, J. R.; Chaves, M. M.; 2003: Partial root-zone drying: Effects on growth and fruit quality of field-grown grapevines (*Vitis vinifera* L.). Funct. Plant Biol. **30**, 663-671.

Schultz, H. R.; 1996: Water relations and photosynthetic responses of two grapevine varieties of different geographical origin during water stress. Acta Hortic. **427**, 251-266.

Schultz, H. R.; 2000: Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV B effects. Aust. J. Grape Wine Res. **6**, 2-12.

Smart, R. E.; Robinson, M.; 1991: Sunlight into Wine. A Handbook for Winegrape Canopy Management. Winetitles, Adelaide, Australia.

Smart, R. E.; Stephen, M. S.; Winchester, R. V.; 1988: Light quality and quantity effects on fruit ripening for Cabernet Sauvignon. Am. J. Enol. Vitic. **39**, 250-258.

Spayd, S. E.; Tarara, J. M.; Mee, D. L.; Ferguson, J. C.; 2002: Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv.Merlot berries. Am. J. Enol. Vitic. **53**, 171-182.

Turner, D. W.; Menzel, C. M.; Simpson, D. R.; 1996: Short term drying of half the root system reduces growth but not water status or photosynthesis in leaves of passionfruit. Sci. Hortic. **65**, 25-36.

Williams, L. E.; Mattews, M. A.; 1990: Grapevine. In: Irrigation of Agricultural Crops. Series of Agronomy, 1019-1055. Madison, Wisconsin, USA.

Received January 27, 2005