Irrig Sci (2008) 26:347–356
DOI 10.1007/s00271-007-0098-4

ORIGINAL PAPER

Evaluation of partial root-zone drying for potential field use as a deficit irrigation technique in commercial vineyards according to two different pipeline layouts

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Received: 3 September 2007 / Accepted: 14 November 2007 / Published online: 11 December 2007

Abstract The use of partial root-drying (PRD) irrigation implies doubling pipelines instead of using a conventional single pipeline. However, pipelines can be spaced a short distance apart (e.g. 1 m) along the vine row ("D" layout) or joined with cable ties and laid as a single pipeline ("S" layout). Pipelines in "S" configuration are laid under the vine row, and in "D" at both sides of the vine row. These two different layouts can change the wetted soil zone and affect grapevine response to irrigation. The focus of this study was therefore on establishing the role of pipeline layout in vine-grape (cv. 'Tempranillo') response under semi-arid conditions in which PRD is managed as a deficit irrigation technique. Six irrigation treatments were applied, which resulted from the combination of Control (C, full irrigation), PRD and seasonal sustained deficit irrigation (SSDI), and "S" and "D" pipeline layouts. SSDI and PRD were irrigated to 50% C throughout the irrigation season, and C irrigation was scheduled according to a crop water balance technique. Midday stem water potential (Ψ_{stem}) and leaf conductance (g_l) indicated that, on the whole, PRD treatments had a slightly higher water status than SSDI treatments, but a substantially lower status than C treatments. Use of the "D" pipeline layout significantly reduced Ψ_{stem} in both PRD and SSDI treatments and in some instances for Control conditions, too. Berry yield, vine intercepted radiation, leaf abscisic acid (ABA) and g_l were highly correlated with Ψ_{stem}. Differences in water status between PRD-S and SSDI-S, according to a sub-surface irrigation test, seemed to be more related to changes in soil evaporation losses and irrigation efficiency than to any intrinsic PRD effect. PRD-S accounted for water savings equivalent to 10% according to the ratio between applied water and grape production for the SSDI-S treatment, whereas PRD-D berry yield was not significantly different from that associated with the SSDI-S treatment. In conclusion, under the growing conditions of this experiment, PRD-S offered the possibility of slightly improving water conservation when irrigation was applied to the soil surface.

Communicated by S. Azam-Ali.

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Introduction

Partial root-drying (PRD) zone is an irrigation technique based on alternately wetting and drying opposite parts of the surface soil under which the plant root system is thought to be located. PRD is commonly applied as part of a deficit irrigation program because it does not require the application of more than 50–70% of the water used in a fully irrigated program. PRD was originally developed in vine-grape plants after root split experiments (Dry and Loveys 1999; Loveys et al. 2000; Dry et al. 2000; Stoll et al. 2000). In vineyards, it has been claimed that PRD helps in controlling excessive vegetative growth and improves grape quality while not reducing fruit production (Loveys et al. 2000). Studies reporting such responses have attributed these effects to the wet part of the root system being moist enough to provide adequate water supply to the part of the plant above ground, and to the dry part of the root system producing a stress signal response, i.e. abscisic concentration (ABA) (Dry et al. 2000; Loveys et al. 2000;

Stoll et al. 2000). Root-produced ABA can rise through the transpiratory system, reducing stomata opening so much that it can disable the coordinated response of leaf conductance and stem water potential (Ψ_{stem}), to water stress. In other words, leaf conductance could be considerably reduced while Ψ_{stem} values may be greater than expected (Loveys et al. 2000). This differential response effect is referred to as only transitory because leaf conductance can recover after 1 week treatment (Loveys et al. 2000).

The PRD technique has been tested in both vine-grapes and deciduous fruit trees under different field growing conditions but full conformity with the general PRD mechanism still has to be achieved under field conditions (Goldhamer et al. 2002; Grant et al. 2004; Leib et al. 2006; Kang et al. 2002). Initial physiological experiments were carried out under controlled conditions and involved a root system split into two separate halves in which irrigation was applied alternatively. In a recent vineyard field study, PRD did not affect leaf conductance, berry yield, or vegetative development, when compared with conventional treatments applying identical quantities of water (Gu et al. 2004). Other recent reports on vineyard production show a similar lack of predicted results for fully irrigated vineyard yield maintenance in comparison with results from traditional deficit irrigated orchards (Bravdo et al. 2004; Chalmers et al. 2004; Pudney and McCarthy 2004). The only exceptions related to field experiments were those conducted under easy drying conditions, such as on sandy soils (de Souza et al. 2003; dos Santos et al. 2003).

On the other hand, there are other aspects that may have an impact on vineyard PRD response at a commercial level. For instance, PRD irrigation involves the use of a double pipeline running along the vine rows. On many occasions, the space between these pipelines is about 1 m, which implies an increase in the wetted soil surface. The importance of the interaction associated with increasing the size of the wetted surface with PRD has not yet been discussed in the literature. The increase in the wetted soil surface may act in two opposing directions. On one hand, it could have a negative impact on the soil water balance in environments with a high evaporative demand and low rainfall and reduce the soil water content. On the other, it could increase the total wetted volume and thus the effective soil volume for root growth, which could improve the vine water status (McClymont et al. 2006).

The present experiment was planned to identify the possible advantages of using PRD as a water conservation technique for vineyard irrigation management under semiarid conditions. With this aim in mind, an effort has been made to isolate the effects of increasing the area of the wetted soil surface by changing pipeline layout design from those related with alternation of irrigation between neighboring pipelines.

Materials and methods

Experimental site

The experiment was conducted over four consecutive years (2003–2006) at a commercial vineyard (*Vitis vinifera* L.) of 9-year-old 'Tempranillo' vines (1.9×3.1 m^2 spacing) (1,900 vines/ha) located at Raïmat, Lleida (Spain): the vines were grafted on SO_4. The orchard was fully irrigated since its initial establishment. The soil texture was that of a silty-loam, and the effective soil depth was 40–95 cm. Average annual rainfall and ETo (Penman-Monteith) for the study period were 358 and 950 mm, respectively. Rainfall was low in 2004, 2005 and 2006 averaging 275 mm, and relatively high during 2003, with 601 mm. However, much of the 2003 rainfall occurred after harvest. Daily maximum temperatures during the summer were about 36–38°C.

Vines were trained to a bi-lateral cordon system at a height of 1 m. Canopy management practices included vertical shoot positioning, in June, and mechanical shoot topping thereafter. Winter pruning was based on leaving 20 spurs per vine in 2003 and at least 15 per vine after 2003. Soil management was based on a no-tillage program with herbicide being applied beneath the vine rows and with inter-row mowing throughout the growing season.

Irrigation treatments

Irrigation water was daily supplied to all experimental vines through a drip irrigation system, with drippers positioned at regular intervals along the pipe. The system was operated by an irrigation controller that individually opened and closed solenoid valves corresponding to each experimental unit at the same moment of the day, early afternoon for all solenoid valves. Irrigation was scheduled on a weekly basis and followed a water balance method (Allen et al. 1998). The main components of the water balance calculation were ETc and $Rain_{ef}$, because there was no water table. Evapotranspiration (ETc) was calculated from ETo Penman-Monteith (Allen et al. 1998) and crop coefficients (Kc) were derived from previous experiments (ETc = ETo (Kc) (Girona et al. 2006). $Kc_1 = 0.2$ (from bud-break on 15th April), $Kc_2 = 0.8$ (mid-season, from veraison on 20th July until harvest), $Kc_3 = 0.3$ (at leaf fall at the end of October). Effective rainfall ($Rain_{ef}$) was estimated as half of the rainfall for a single event-day with more than 10 mm of precipitation: it was otherwise considered to be zero. Meteorological data were gathered from an automated weather station furnished with the necessary sensors required for the Penman-Monteith calculation. The meteorological station was located 1 km from the experiment site.

The irrigation treatment applied considered two different levels of irrigation; full irrigation (Control) and deficit irrigation (50% Control), throughout the irrigation season. Deficit irrigation was applied by two different techniques: (1) seasonal sustained deficit irrigation (SSDI) and (2) partial root-drying (PRD). The drip pipelines were also set up in two different ways. The simple, or traditional, configuration involved the use of only one pipeline per vine row (S), whereas in the other applications, two pipelines per row were used and spaced 1 m apart (D). With the D configuration, there was no overlap of wetted soil surface zones between the two sides of each row. As drip PRD involves the use of two pipelines per vine row, in the case of the simple configuration (PRD-S), the two pipelines were joined and placed underneath each vine row. There were alternate zones with (placed every 53 cm, with 3 emitters per 2.1 m length) and without emitters (every 2.1 m) in order to create dry and wet zones within each vine row (Fig. 1). Water flow was alternated between the pipelines every 3 weeks.

Combining the three factors considered in this experiment, i.e. applied water, deficit irrigation (PRD vs. SSDI) and soil surface wetted area (S vs. D), produced the six irrigation treatments applied:

1. Control-D. Full irrigation with two pipelines spaced 1 m from each vine row.
2. Control-S. Full irrigation with one pipeline beneath each vine row.
3. PRD-D. Irrigation at 50% of the Control value with flow alternating between two pipelines spaced 1 m from each vine row.
4. PRD-S. Irrigation at 50% of the Control value with flow alternating between two joined pipelines positioned beneath each vine row.
5. SSDI-D. Irrigation at 50% of the Control value with two pipelines spaced 1 m from each vine row.
6. SSDI-S. Irrigation at 50% of the Control value with one pipeline positioned beneath each vine row.

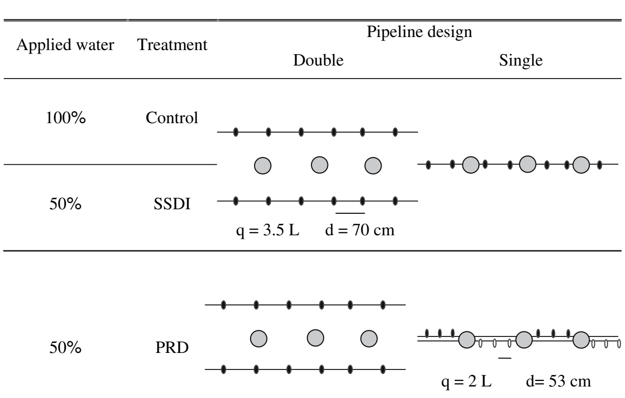

Fig. 1 Irrigation treatment definitions and different pipeline designs

The experimental layout was a randomized complete-block design with four block-replicates per treatment. Each of the 24 experimental plots consisted of four adjacent rows of vines with ten vines per row. The six central vines of the two central rows were monitored while the others served as guard vines.

Measurements

The volume of applied irrigation water was determined by reading the water meters on each experimental plot on a daily basis. This was done to verify that the quantities of irrigation water applied were as previously defined.

Midday stem water potential (Ψ_{stem}) was measured with a pressure chamber (Soil Moisture plant water status console 3005 Corp. Sta. Barbara, CA, USA) following recommendations by Shackel et al. (1997). To ensure a balance between the leaf and the stem attached to it, leaves located near the main trunk were bagged for 1 h before taking the readings. All measurements were taken in less than an hour, with two leaves being measured per experimental unit (one from each row). A total of 13–15 measured-days per year (once per week) were recorded for each experimental plot. Leaf conductance (g_l) was determined with a "steady state" porometer (model Li -1600, LICOR, Lincoln, NE, USA). Measurements were taken from three mature, completely illuminated, leaves per experimental plot.

The fraction of PAR light intercepted by the crop (FIR) was determined as an indicator of vegetative development using a ceptometer (Accupar, Decagon Devices Inc, Pullman, WA, USA). Data were gathered on a 12-point grid measured at ground level. Each grid was located in the central part of each individual plot and contained no border vines. Incident radiation readings were taken above the vines. Light measurements were taken once a year, in mid-July, at midday and at intervals of less than 1.5 h.

Leaf ABA content was measured according to the method described in Vilaró et al. (2006). Briefly stated, on 2nd August 2003, three mature sun-lit leaves were collected, at midday, from each experimental vine and grouped by experimental plot. Each sample group was immediately frozen in liquid nitrogen, lyophilized and milled to obtain a fine powder. For ABA quantification, the samples were then submitted to solid–liquid extraction and analyzed by high-performance liquid chromatography electrospray ionization-mass spectrometry in ion monitoring mode, using a stable isotope-labeled ABA as an internal standard.

Harvest was carried out during the second week of September. Experimental vines were hand harvested. Clusters for each vine were counted and total vine yield was weighed. Cluster fresh weight was estimated as vine yield divided by cluster number per vine. A sample of 100 berries per experimental plot was taken to the laboratory. The

Table 1 Yearly average values for midday stem water potential and leaf conductance in response to the year of the experiment and irrigation treatment

Year	Irrigation treatment	Physiological parameters		
		Ψ_{stem} (MPa)	g_l (mmol m^{-2} s^{-1})	FIR (%)
2003	C-S	−0.84 a[2]	242 a	0.28
	C-D	−0.97 b	182 b	0.27
	PRD-S	−1.00 b	161 bc	0.26
	PRD-D	−1.11 c	141 cd	0.28
	SSDI-S	−1.16 c	115 d	0.23
	SSDI-D	−1.29 d	116 d	0.25
	ANOVA[1]	***	***	NS
2004	C-S	−0.81 a	179 a	0.38 a
	C-D	−0.82 a	164 b	0.37 a
	PRD-S	−0.92 b	124 c	0.31 b
	PRD-D	−1.05 c	104 d	0.27 bc
	SSDI-S	−1.03 c	113 cd	0.25 c
	SSDI-D	−1.12 d	106 d	0.26 c
	ANOVA	***	***	***
2005	C-S	−0.70 a	209 a	0.30 a
	C-D	−0.75 a	186 b	0.25 abc
	PRD-S	−0.83 b	173 b	0.26 ba
	PRD-D	−0.98 c	130 cd	0.19 cd
	SSDI-S	−0.94 c	139 c	0.21 bcd
	SSDI-D	−1.11 d	118 d	0.16 d
	ANOVA	***	***	***

Different letters mean significant differences at $P < 0.05$ using Duncan's test

FIR fraction of crop intercepted radiation at midday

[1] NS, *, **, *** Non-significant or significant at $P < 0.05$, 0.01, or 0.001, respectively, by ANOVA split-plot in time, and with complete randomized blocks

[2] Significant at $P = 0.05$ using Duncan's test (SAS institute, 1988)

berries were then dried in a forced air draft oven, regulated at 70°C, until they acquired a constant weight. Relative dry weight (RDM) was calculated as dry divided by fresh weight.

Sub-surface drip irrigation test

In 2006, and in one replication-block, PRD-S vines and SSDI-S vines were converted to subsurface drip irrigation treatments (SDI) without changing the original irrigation scheduling corresponding to each treatment (SDI-PRD-S, SDI-SSDI-S). For this purpose, the standard pipelines were replaced by new pipelines adapted for subsurface use (UNIRAM, Netafim, Israel) and dug (to a depth of 0.3 m) into the soil profile. A 2-m wide plastic cover was placed on the soil surface over the buried pipeline. The switch from above-surface to sub-surface irrigation took place on 27th June 2006. The effect of switching to SDI on midday stem water potential was monitored in subsequent weeks using the same measurement technique described earlier, but doubling the sample size per experimental plot. The combination of SDI and the plastic cover should have prevented any loss of soil evaporation from water supplied by the irrigation system.

Results

The different irrigation rates had a significant effect on midday Ψ_{stem} values. Maximum differences between treatments and minimum values in Ψ_{stem} were found in 2003, with differences between extreme treatments, such as Control-S versus SSDI-D, being as great as −0.6 MPa (Table 1; Fig. 2). In 2004 and 2005, differences between treatments

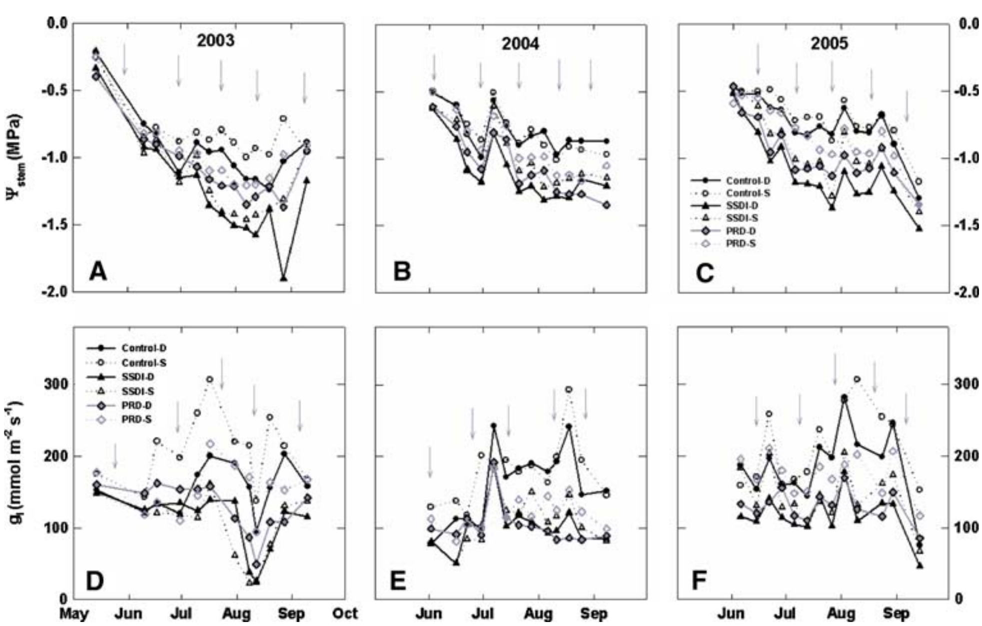

Fig. 2 Seasonal variations in (a, b, c) midday stem water potential (Ψ_{stem}) and (**d**, **e**, **f**) leaf conductance (g_l) of trees receiving the different irrigation treatments during 2003 (**a**, **d**), 2004 (**b**, **e**) and 2005 (**c**, **f**). Each value is the mean of 8 measurements. *Arrow* indicates the moment of irrigation alternation between neighboring pipelines in PRD treatments

and minimum Ψ_{stem} values were more moderate (Table 1; Fig. 2). Seasonal trends in Ψ_{stem} revealed a tendency for values to decrease from late spring until the end of the summer for all irrigated treatments, although spring-to-summer decreases were most evident in plants irrigated under deficit conditions (PRD and SSDI) (Fig. 2). PRD treatments (PRD-S and PRD-D) demonstrated clear tendencies towards slightly higher Ψ_{stem} values than SSDI treatments. Significant differences in yearly averages were found between PRD-S and SSDI-S, although PRD-S values were closer to SSDI than to the Control treatment vines (Table 1; Fig. 2). With regard to the influence of irrigating with a double (D) rather than a single (S) pipeline, it was found that there were clear differences between the two deficit irrigation strategies (PRD, SSDI), and the double pipeline helped to reduce Ψ_{stem} values (Table 1). This pattern was observed for all experimental years and also for the Control treatment in 2003 (Table 1).

Irrigation treatments induced highly significant differences in leaf conductance (g_l) (Table 1; Fig. 2). These differences were very similar to those observed in Ψ_{stem}; the highest and minimum values were found for the Control-S and SSDI-D treatments, respectively, and in-between values were recorded for the two PRD treatments (Table 1; Fig. 2). The effect of using a double instead of a single pipeline also produced significant effects on g_l; the double pipeline reduced g_l in the same way that Ψ_{stem} was reduced (Table 1; Fig. 2). The two parameters g_l and Ψ_{stem} evolved hand in hand with the imposition of water stress, exhibiting a negative exponential relationship (Fig. 3). In these relationships, an upshift was observed for data corresponding to 2003 as opposed to 2004 and 2005 (Fig. 3).

No significant effects on g_l and Ψ_{stem} were observed immediately when alternating irrigation applied to PRD-S and PRD-D vines was compared with well-irrigated treatments (Control-S and Control-D) (Fig. 2). During the first 10 days following alternating irrigation, no clear transitory decrease was observed for g_l values (Fig. 4). Leaf ABA concentration was strongly correlated with Ψ_{stem} and, to a lesser extent, with g_l on 2nd August 2003 (Fig. 5). All ABA observations were aligned with a single linear tendency for the relationship with Ψ_{stem} and g_l (Fig. 5).

The fraction of intercepted PAR (FIR), which could be an indicator of final vine size when measured once vegetative growth had ceased, presented clear differences between irrigation treatments for all years except 2003 (Table 1). After 2003, average control values for FIR were about 25% greater than those for SSDI treatments (Table 1). Variations in FIR among different irrigation treatments were highly correlated with average Ψ_{stem} (Fig. 6).

The effect of different irrigation treatments on grape yields was noticeable (Table 2). Reducing the quantum of applied water by half in the SSDI treatments was associated with an average 40% reduction in grape yield (Table 2). However, the interaction Treatment × Year was significant for yield components (Table 2). This interaction can be at least partially explained by the change in vineyard management and winter pruning after 2003, which was aimed at reducing berry yield and improving quality (Fig. 7). The yearly evolution of berry yield shows slight differential alternate bearing after 2003 between C-S and PRD-D vines (Fig. 7). This alternate bearing was apparently not a problem because year-to-year analyses showed consistent yield differences between irrigation treatments throughout the 4 years of the experiment (Table 2). The response of PRD to grape yield fell between those of the Control and SSDI treatment vines (Table 2). No significant differences were observed between irrigation treatments in terms of the number of clusters present per vine until the third year of the experiment, when the PRD and SSDI treatments produced a slight decrease in cluster numbers (Table 2). Average grape yield values for the experimental period presented a strong lineal correlation with average Ψ_{stem} (Fig. 8b). However, applied water demonstrated a weaker relationship with average grape yield than with Ψ_{stem} (Fig. 8a).

The sub-surface irrigation test indicated that previously observed differences in Ψ_{stem} values between SSDI-S and PRD-S disappeared 2 weeks after switching from surface to subsurface irrigation systems (Fig. 9).

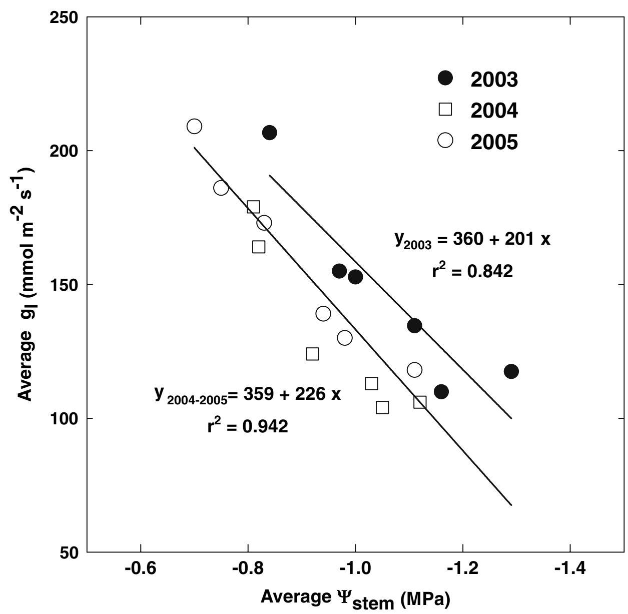

Fig. 3 Relationship between midday stem water potential (Ψ_{stem}) and leaf conductance (g_l) for the different years of experiment (2003, 2004, 2005). Relationships for 2004 and 2005 are fitted to a single exponential function. Each value is the annual treatment average

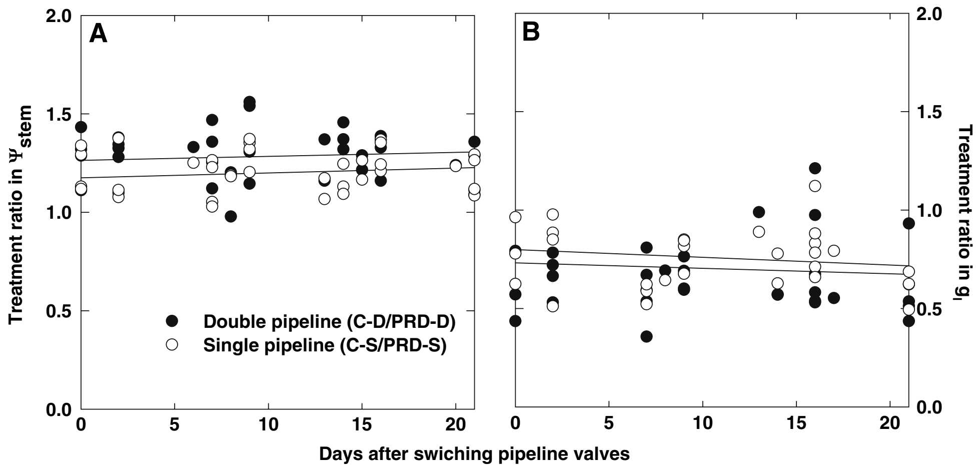

Fig. 4 Daily variation in **a** midday stem water potential (Ψ_{stem}) and **b** leaf conductance (g_l) expressed as treatment ratios between Control and PRD treatments for the two considered pipeline designs (C-S/PRD-S, and C-D/PRD-D). The days considered are those within periods of irrigation alternation for 2003, 2004 and 2005 years of experiment. Each value is the ratio between irrigation treatment daily means

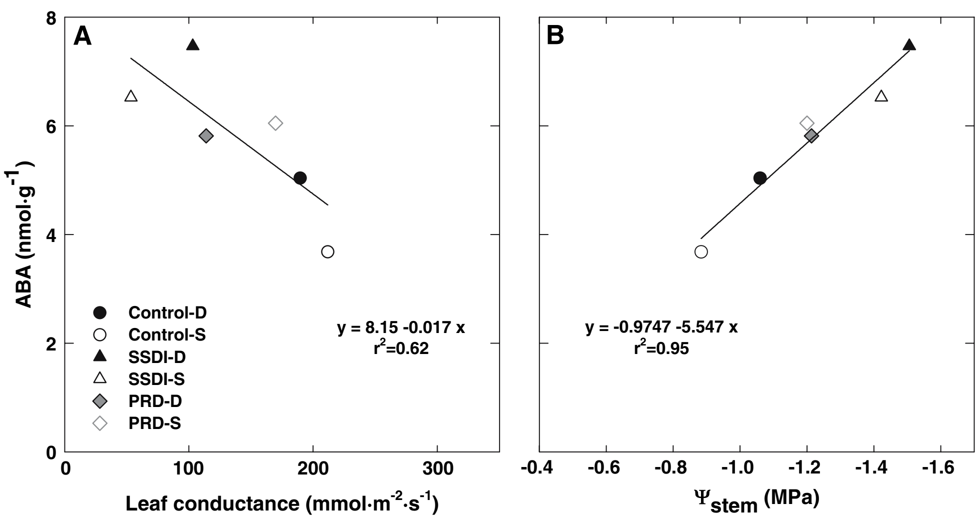

Fig. 5 Relationships between leaf acid abscisic (ABA) and (**a**) leaf conductance (g_l) and (**b**) midday stem water potential (Ψ_{stem}) and corresponding to the measurement taken on 2nd August 2003. Each value is the mean of 8 measurements per irrigation treatment

Discussion

None of the altered physiological responses reported by Loveys et al. (2000), as indicative of a PRD plant response and also described in cv. 'Tempranillo' (Antolin et al. 2006), were observed under the conditions of this experiment. This accounted for: (1) transitory decreases in g_l for PRD vines shortly after irrigation alternation, (2) maintenance of Ψ_{stem} in PRD vines at similar levels to those of Control vines, and (3) reductions in vegetative growth in PRD vines without parallel reductions in fruit growth. In our study, no transitory declines in g_l were observed for PRD vines, Ψ_{stem} values for PRD vines were significantly lower than their Control counterparts, and reductions in both canopy development (estimated from midday FIR) and final berry size were generally observed throughout the experiment (Figs. 4, 6; Table 1). Furthermore, ABA leaf content for PRD samples was not proportionally higher than that associated with SSDI treatments, in terms of average Ψ_{stem} of the day of sampling. Similarly to what has been reported in deficit irrigation experiments (Girona et al. 2003; Goldhamer and Viveros 2000; Marsal et al. 1997, 2000, 2002; Naor 1998, 2006), g_l and Ψ_{stem} were very well coupled on a daily basis. However, a relationship considering average annual data showed a shift towards higher g_l in 2003 (Fig. 3). This shift was associated with higher berry load conditions for that year (Fig. 7).

Unlike in experiments involving containers, in the real farming world, root systems cannot be split into two and, in many cases, periods of alternating irrigation may not be shorter than 2 weeks: it takes longer for a root system to deplete water in a large portion of mineral soil than in small containers. Considering that PRD authors reported transitory g_l declines as a temporary effect, lasting only 1 week (Loveys et al. 2000), a possible explanation for our findings could be the role of the slow drying path in generating partial root-zone drying. This may have been too slow to permit ABA generated by the root system having a clear influence on g_l (as a 3 week period was required in our study to alternate irrigation in PRD treatments). The low degree of control in field experiments over the different parts of the root system can also be a feasible explanation

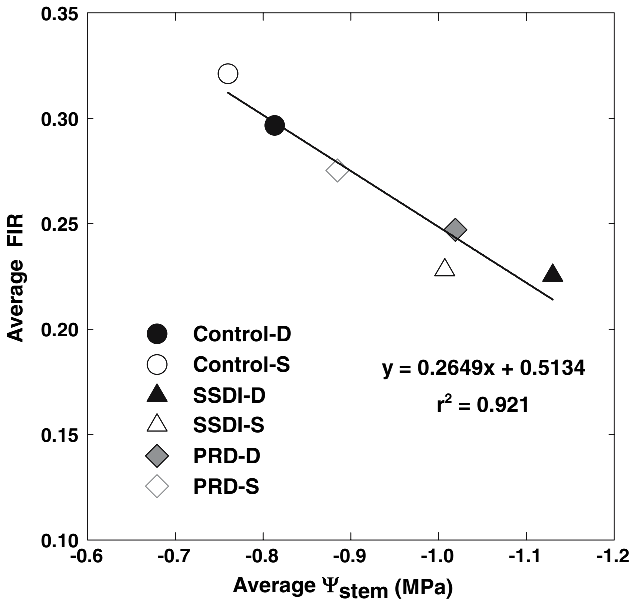

Fig. 6 Relationship between annual average of midday stem water potential (Ψ_{stem}) and the fraction of midday photosynthetic intercepted radiation (FIR) by the vines subjected to different irrigation treatments for a specific day after veraison. Each value is the mean of three annual treatment averages corresponding to the 2003, 2004 and 2005 years of experiment

for other studies not showing the typically PRD altered physiology (Gu et al. 2004; Chalmers et al. 2004; Pudney and McCarthy 2004), whereas in cases where this control can be improved such as in sandy soils, the PRD response is favored (de Souza et al. 2003; dos Santos et al. 2003). The differences in the timings of the treatments applied between controlled and field-growing experiments constitute an inherent problem for extrapolating results from environmentally controlled experiments to commercial orchard conditions.

Because of the described decoupling between g_l and Ψ_{stem} under PRD (Loveys et al. 2000), at the moment of starting the experiment it was not clear which parameter, Ψ_{stem} or g_l, was going to be the most reliable indicator of water stress. Correlations of Ψ_{stem} and g_l with berry production indicated greater significance with Ψ_{stem} than with g_l (data not shown). Another reason for this initial uncertainty was that 'Tempranillo' has been reported as a cultivar with variable isohydric characteristics: these characteristics were evident in Intrigliolo and Castel (2006) but almost absent in Yuste et al. (2004). In our experiment, 'Tempranillo' behaved more like an anisohydric cultivar, and there was a sharp distinction between the midday Ψ_{stem} values of the irrigation treatments (Fig. 2). PRD irrigation did not alter the covariance between Ψ_{stem} and g_l that typically occurs as water stress develops as part of an isohydric response. Schultz (2003) described isohydric characteristics as more of a genetic factor at the species level and in the specific case of vine-grapes as a characteristic also observed at the cultivar level. However, the large differences in Ψ_{stem} values associated with different treatments observed in numerous measurements taken over the 3 years of the experiment make it reasonable to also consider other factors. In our experiment, the orchards had been fully irrigated since their initial establishment, which was not the case in other studies in which vineyards were sometimes established in dry areas and irrigation was implemented later, either as a supplemental or a fully irrigated strategy (Intrigliolo and Castel 2006).

Table 2 Analysis of variance for grape yield components and their average estimates for the experimental period 2003–2006

Source	DF	Error term for *F* test	*P* > *F* Grape yield	Cluster count	Cluster fresh weight
Treatment (T)	5	B × T	0.0001	0.0251	0.0001
Block (B)	3	B × T	0.1786	0.0144	0.9701
B × T	15	Y × B × T	0.0840	0.3119	0.1501
Year (Y)	3	Y × B × T	0.0002	0.0001	0.0001
Y × T	15	Y × B × T	0.0106	0.0063	0.0128
Y × B	8	Y × B × T	0.0070	0.1611	0.0256
Y × B × T	40	Residual	0.5446	0.4808	0.1254
Residual	843				

Irrigation treatments	Grape yield (kg vine^{-1})	Cluster count (# cluster vine^{-1})	Cluster fresh weight (g)
C-S	13.1 a	45 a	297 a
C-D	11.2 b	41 ab	281 ab
PRD-S	9.2 c	39 b	249 b
PRD-D	7.1 d	37 b	194 cd
SSDI-S	7.4 d	37 b	212 c
SSDI-D	6.1 d	36 b	176 d

Different letters mean significant differences at $P < 0.05$ using Duncan's test (SAS institute, 1988)

The final results obtained in this study suggested that a significant relationship was found in all cases in which Ψ_{stem} was used as an indicator of vine water status. Examples of this can be seen for berry production (Fig. 8b), vine-intercepted radiation (Fig. 6) and grape quality characteristics (dry matter, soluble solids, anthocyanins), which were evaluated in parallel studies (Olivo 2007).

As Ψ_{stem} values distinctively differentiate between irrigation treatments, a yield reduction pattern for the different treatments was also found (Table 2). This occurred despite the observed yield reductions varied from 2003 to 2005 (in 2003, they were more related to the effect of cluster dehydration and were also influenced by the reduced number of clusters per vine in 2005). However, cumulative applied water was far less effective for predicting berry yield than Ψ_{stem} (Fig. 8). This was probably due to variations in irriga-

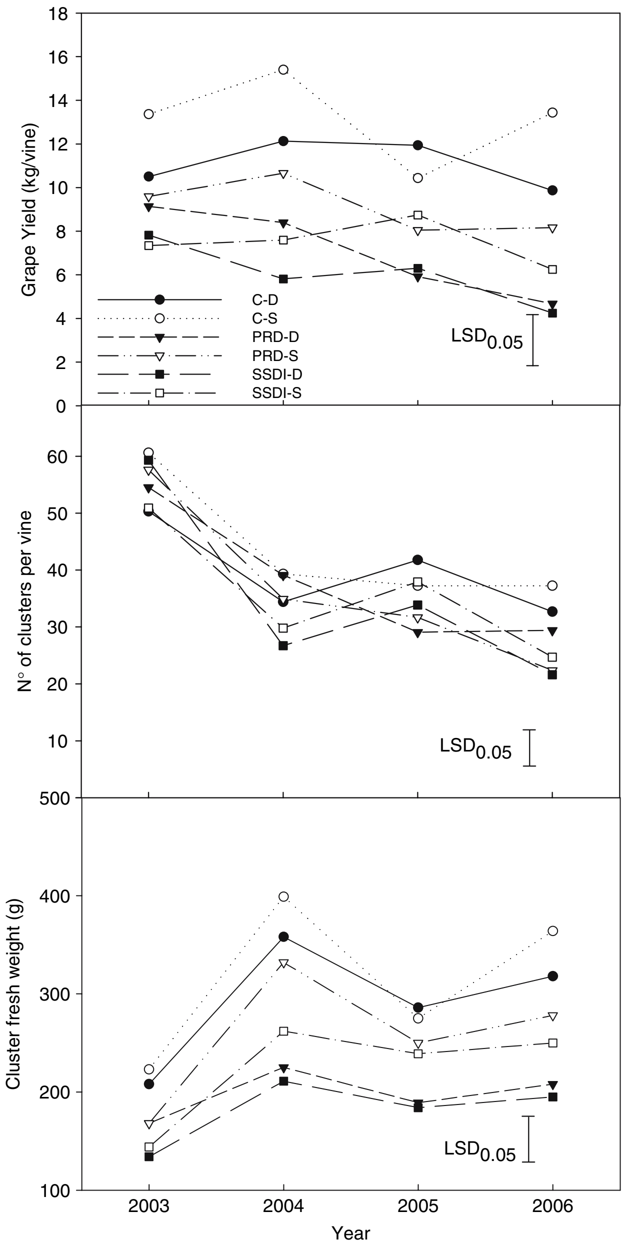

Fig. 7 Yearly evolution in grape yield (**a**), number of clusters per vine (**b**) and cluster fresh weight (**c**) in response to the different irrigation treatments. Each value is the mean of 48 plant measurements per irrigation treatment. The *error bar* indicates the Least Square Difference (LSD) at a probability level of 5% for 2006 year of experiment

tion efficiency relating to different pipeline distributions (i.e. SSDI-S vs. SSDI-D, and PRD-S vs. PRD-D) and also to the use of PRD. In both cases, possible differences in irrigation efficiency were related to significant differences in Ψ_{stem} values for equal levels of applied water (Table 2). For instance, in the case of PRD-S versus SSDI-S, using PRD-S vines produced higher Ψ_{stem} values and slightly larger berry yields. In fact, in PRD-S irrigation at the surface level, the wetted soil surface zone was typically composed of a wet strip divided by dry zones, whereas in SSDI-S irrigation, the wetted strip was always continuous. Based on the apparent size of the wetted soil area from a sample of wet strip bands, PRD-S produced 9 and 17% larger wetted surfaces with respect to vine spacing measured the day before and 4 days after alternating the irrigation. SSDI-S consistently produced a 14% wetted surface during summer (data not shown). For most of the alternation irrigation period (3 weeks), the PRD-S soil surface was therefore less exposed to soil evaporation than that of SSDI-S. The only exception to this tendency was observed in the 2–3 days immediately after alternating irrigation, when both sides of the PRD-S vines had wetted soil surfaces. The sub-surface irrigation trial was designed to test the hypothesis that differences in soil evaporation could change irrigation efficiency with PRD irrigation. When PRD-S and SSDI-S were switched from surface to sub-surface irrigation, earlier advantages in Ψ_{stem} for PRD-S, as opposed to SSDI-S, disappeared completely (Fig. 9). This would seem to confirm that PRD treatment had the effect of reducing the soil evaporation component with respect to SSDI-S. In our study, the irrigation efficiency effect was probably greater than under other growing conditions because the soil was managed by applying strip herbicides and without tilling. This resulted in a type of crust becoming apparent on the top soil layer. This slightly crusty top layer may induce some extra water movement at the soil surface and could perhaps also make the system more prone to lower irrigation efficiency.

It should also be considered that as vineyards have low canopy cover in comparison with deciduous orchards, soil evaporation is a more important component of their ET. Previous vineyard studies indicate that soil evaporation could account for between 50 and 70% of total ETc (Lascano et al. 1992; Heilman et al. 1994). These values are probably too high for the conditions of the present experiment for drip-irrigated vines in which the wetted soil surface zone falls under vine-row shadow for most of the day. Furthermore, the central parts of the isles are usually dry during the summer season, when rainfall is normally absent. Even when soil evaporation rates are lower than 50%, their influence cannot be neglected and they may explain reductions in berry production for D pipeline layouts for any applied water strategy. In our experiments, the D pipeline layout produced a doubling of the wetted soil surface zone. Furthermore, wetted zones were exposed to direct sunlight at midday which, under the semi-arid conditions and low canopy cover of this experiment, may have increased soil evaporation and thus reduced water availability to plant roots. This could explain why vines irrigated using the D pipeline configuration reduced Ψ_{stem} and g_l in comparison with similar configurations employing the S layout.

In summary, despite the common belief among viticulturists that increasing the wetted soil surface can increase

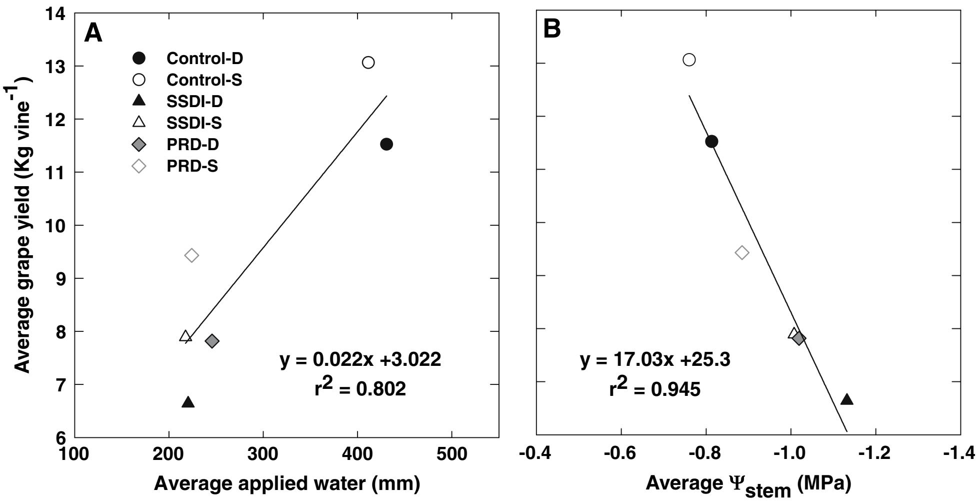

Fig. 8 Relationships between grape yield and (**a**) annual applied water and (**b**) annual average midday stem water potential (Ψ_{stem}). Each value is the mean of 3 years of experiment (2003, 2004 and 2005) considering 8 annual averages per irrigation treatment and year

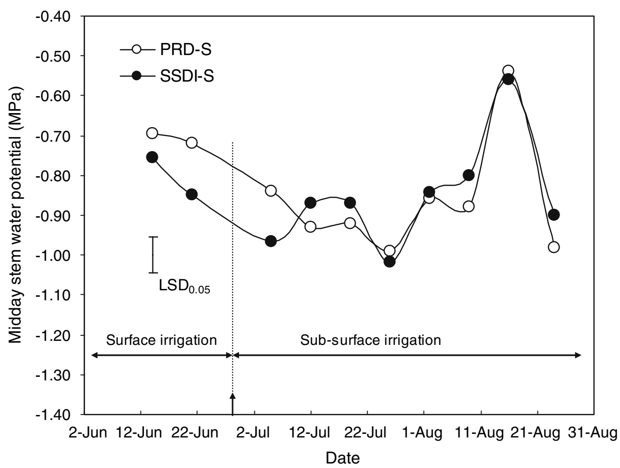

Fig. 9 Daily evolution in midday stem water potential in response to PRD-S and SSDI-S irrigation treatments before and after switching irrigation from surface to sub-surface application during year of experiment 2006. Each value is the mean of four measurements. The *error bar* indicates the Least Square Difference (LSD) at a probability level of 5%

vigor and grape yield, this experiment proved that D systems reduced vine water status, vigor and yield. We hypothesize that these reductions in yield could be related to a decrease in irrigation efficiency. Generally speaking, a qualitative linkage was observed between the reduction in size of the wetted soil surface and accrued advantages for grape production (PRD-S > SSDI-S > SSDI-D). According to the sub-surface irrigation test, the main reason for the apparent superiority of PRD-S over SSDI-S was the greater irrigation efficiency of the former system. The results of this experiment suggest that PRD-S could make a significant contribution to water conservation for cropping systems with low canopy cover under semi-arid environments. According to the ratio between applied water and grape production for an S pipeline layout, the increase in yield associated with PRD-S as opposed to SSDI-S accounted for a water savings equivalent to 10%.

Acknowledgments The authors would like to thank Raïmat Wineries, and particularly X. Farré and J. Esteve, for allowing this research activity in their vineyards under IRTA-Codorniu agreement (Unitat Mixta Codorniu-IRTA). The authors would like to thank J.R. Solans, G. Lopez, M. Elias, V. Reyes and A. Mata for field assistance. This study was funded by the Spanish National Institute for Agriculture Research (INIA-VIN02-17). N. Olivo received an FPI grant from INIA.

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