EFFECT OF DIFFERENT IRRIGATION STRATEGIES ON VINE PHYSIOLOGY, YIELD, GRAPE COMPOSITION AND SENSORY PROFILE OF SAUVIGNON BLANC (*VITIS VINIFERA* L.) IN A COOL CLIMATE AREA

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Abstract

Aim: The impacts of partial root zone drying (PRD) and regulated deficit irrigation (RDI) on soil moisture, vine water status, yield components, fruit composition and wine sensory profile of Sauvignon blanc were studied in a cool climate region.

Methods and results: Field experiments were conducted in a commercial Sauvignon blanc block in Ontario, Canada between 2006 and 2008. Treatments were: non-irrigated control, PRD, full irrigation [100% of crop evapotranspiration (ET_c)] and one level of RDI (25% ET_c). Treatments began immediately after fruit set and continued until the beginning of September. Reference evapotranspiration (ET_o) was calculated using the Penman–Monteith equation. Soil moisture and vine water status (leaf water potential and transpiration rate) in the PRD treatments were generally less than in 100% ET_c but higher than in non-irrigated and 25% ET_c treatments. Almost all treatments were different than non-irrigated vines in fruit composition and wine sensory attributes. RDI strategies were more consistent across vintages than the PRD treatments in their effect on vine water status, grape composition and sensory profiles.

Conclusions: Use of RDI or PRD in cool climates during dry and warm years can improve grape composition. In very dry and hot seasons, like that of 2007, irrigation improved grape composition and wine aroma typicity. RDI enhanced fruity aroma attributes, which suggests that this could be a viable strategy to improve grape and wine quality in cool areas. However, due to high climatic variation over the period studied, no consistent pattern of irrigation effects was found for berry composition, suggesting that plant water status was not the only factor that controlled fruit and wine quality.

Significance and impact of the study: To the best of our knowledge, this study is the first evaluation of PRD in a cool, humid climate, and highlights the potential value of both RDI and PRD irrigation techniques in cool climate regions, particularly during dry growing seasons.

Key words: soil moisture, leaf water potential, regulated deficit irrigation, partial root zone drying, wine sensory profiles

Résumé

Objectif : Les impacts de la déshydratation partielle de la zone racine (PRD) et de l'irrigation déficitaire réglementée (RDI) sur l'humidité du sol, l'état hydrique de la vigne, les composantes du rendement, la composition des fruits et le profil sensoriel des vins de Sauvignon blanc ont été étudiés dans une région au climat tempéré.

Méthodes et résultats : Les expérimentations ont été menées dans un bloc commercial de Sauvignon blanc en Ontario, au Canada entre 2006 et 2008. Les traitements étaient les suivants : témoin non-irrigué, PRD, irrigation complète [100% de l'évapotranspiration des cultures (ET_c)] et un niveau de RDI (25% ET_c). Les traitements ont commencé immédiatement après la nouaison et se sont poursuivis jusqu'au début de septembre. L'évapotranspiration de référence (ET_o) a été calculée en utilisant l'équation de Penman-Monteith. L'humidité du sol et l'état hydrique de la vigne (potentiel hydrique foliaire et taux de transpiration) dans les traitements PRD étaient généralement inférieurs à 100% ET_c mais plus élevés que le témoin et les plantes avec un ET_c à 25%. La majorité des plantes traitées a révélé un profile différent de celui observé sur les vignes non irriguées quant à la composition des fruits et des attributs sensoriels des vins. Les stratégies de RDI se sont avérées plus uniformes que les traitements PRD en ce qui concerne leur effet sur l'état hydrique de la vigne, la composition du raisin et les profils sensoriels des différents millésimes analysés.

Conclusions : L'utilisation de RDI ou PRD dans les climats tempérés pendant les années sèches et chaudes peut améliorer la composition biochimique des baies de raisin. Au cours des saisons très sèches et chaudes, comme celle de 2007, la composition du raisin et la typicité aromatique du vin a été amélioré. Les avantages du traitement RDI sur les arômes fruités pourraient positionner cette technique comme une stratégie viable pour améliorer la qualité du vin et des raisins dans les zones tempérées.

Signification et impact de l'étude : À notre connaissance, cette étude est la première évaluation du PRD dans un climat tempéré et humide, et souligne la valeur potentielle des deux traitements RDI (100% et 25% ET_c) ainsi que celle du PRD dans les régions tempérées avec des épisodes de sècheresse au cours de la saison.

Mots clés : humidité du sol, potentiel hydrique foliaire, irrigation déficitaire réglementée, déshydratation partielle de la zone racine, profils sensoriels des vins

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INTRODUCTION

Vine development and fruit composition are highly dependent on environmental conditions, and particularly on water and nutrients (Jackson and Lombard, 1993). Until recently vineyards were irrigated mostly in the "New World", while in the "Old World" irrigation was prohibited by law. In areas where irrigation was not allowed or not needed, drip irrigation has been steadily increasing. In the last decade many wine regions including some from cool climate areas have faced some degree of water stress during the growing season (Van Leeuwen and Seguin, 2006). The Niagara Peninsula, arguably the most important grape growing region in Canada, is one of these regions (Reynolds, 2008).

Many studies have shown that vine water status is the main factor by which the *terroir* affects wine style and quality (Van Leeuwen and Seguin, 2006). In wine production neither deficit nor excess of water status is desired for an optimum balance of yield and wine quality (Van Leeuwen and Seguin, 2006). Excessive water stress inhibits many late season flavour development processes, and leads to wines with little fruit aroma characteristics (Lakso and Pool, 2001).

Physiological responses of grapevines to prolonged water deficits include reduced cell division and expansion, closing of stomata, reduced photosynthesis and, eventually, cell desiccation and death (Goodwin, 2002). Mild water deficits are known to reduce cell size if applied at fruit set, and thus can enhance the concentration of aroma compounds in berries as long as other metabolic processes are not negatively affected (Smart *et al.*, 1974). Moderate water deficits also reduce shoot vigour, resulting in more favourable partitioning of carbohydrates to the clusters (Keller, 2005). Some studies focused on the influence of water deficits on vine development and yield (Dry *et al.*, 1996) and on fruit composition (Dry *et al.*, 2001; Matthews and Anderson, 1988). In most circumstances, reduction in vine size by PRD led to enhanced cluster microclimate and a concomitant improvement in berry composition. However, most of these studies were carried out on red grape cultivars, and few focused on the effect of water status on vine performance and wine quality.

Grapevine sensitivity to seasonal water deficits and the consequences for vegetative and reproductive growth, must and wine quality are well known (Williams and Matthews, 1990). Very little has been published on the influence of environmental conditions on quality potential in white grapes, especially in regions with cool climates. In a study on Sauvignon blanc in the Pessac-Léognan and Graves appellations, grape aroma potential was highest in vines under mild water deficits and moderate nitrogen supply (Peyrot des Gachons *et al.*, 2005). Severe water deficit stress limited aroma potential, as did nitrogen deficiency.

Sauvignon blanc is a popular white grape cultivar in the Niagara Peninsula, being third in importance after Chardonnay and Riesling (http://www.grapegrowers-ofontario.com), with a yield of 1256 t in 2009. Despite widespread controversy in Ontario on the necessity of using irrigation to obtain premium wines, and due to increased frequency of dry periods during the growing season, growers in cool, humid regions such as Ontario have reconsidered use of irrigation in their vineyards.

One way to improve water use efficiency is through application of regulated deficit irrigation (RDI). If managed properly, RDI can have minimal impact on carbon assimilation or stomatal conductance, despite lowering the total amount of water applied as compared to full irrigation (De Souza *et al.*, 2003). RDI has been widely evaluated worldwide, and is a viable practice in vineyards for controlling excess vigour, reducing pest populations and disease pressure, and improving wine quality (Dry *et al.*, 1996; Smart and Coombe, 1983; Van Zyl, 1984; Williams and Matthews, 1990). Deficit irrigation applied by partial root zone drying (PRD) involves application of a reduced amount of irrigation to alternate sides of the vine (Dry *et al.*, 2000a,b; 2001). In PRD, the root zone is simultaneously wetted and dried, maintaining a relatively high leaf water potential (ψ) close to values obtained in full irrigation treatments. However, the water use efficiency is improved through increases in xylem abscisic acid (ABA) concentration, and concomitant effects on stomatal conductance (Stoll *et al.*, 2000a,b).

The PRD strategy was developed from observations that increases in ABA concentration produced in the drying roots reduced stomatal conductance and vegetative growth (Dry and Loveys, 1999; Dry *et al.*, 2000a,b; Loveys, 1984). Less data are available from field studies (Dry *et al.*, 2000a,b; 2001), and recent results indicate discrepancies between container and field experiments (Pudney and McCarthy, 2004). However, there is still debate on PRD strategy and its effects on grape composition. In most studies, amounts of water used in PRD treatments were a fraction of full irrigation treatments, and confusion persists on this strategy. Does the PRD treatment affect the grapes through the alternating dry and wet root zones or through the deficit water status deliberately created in the wet zone? The objectives of this research were to study effects of different levels of water status imposed by RDI and PRD irrigation strategies on vine physiology, yield components, grape composition, and wine sensory profile of Sauvignon blanc in a cool climate area.

MATERIALS AND METHODS

1. Site description and experimental design

The experiments were carried out over three seasons (2006 to 2008) in a commercial vineyard (Lambert Vineyards Ltd.) in Niagara-on-the-Lake, Ontario (43°13' N, 79°08' W, elevation 98 m), Canada. The trials were set up in a Sauvignon blanc block (23 rows in total), grafted on SO4 rootstock. Vines were spaced at 1.2 m X 2.7 m (3086 vines/ha), trained to a double Guyot system, and vertically-shoot positioned. Row orientation was north-to-south. Soil management consisted of annual application of 25 t/ha fresh dairy manure, with floor management of alternate rows of annual ryegrass and clean cultivation. Pest control was in accordance with local recommendations from Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA, 2007). The soil series was Chinguacousy clay loam with generalized characteristics as follows: a gleyed brunisolic grey brown luvisol with imperfect drainage (7 to 9 L/h); wilting point of the Ap horizon (0 to 27 cm) was 13.3% moisture; field capacity was 27.3% moisture; bulk density increased from 1.25 g/cm^3 in horizon A to 1.69 g/cm^3 in horizon C (Kingston and Presant, 1989). The block was tile drained, with tiles placed at ≈ 60 cm depth in the middle of each inter-row space.

The experimental design was a randomized complete block, with four irrigation treatments each replicated four times, with two rows on each side of each plot as a buffer. Irrigation was initiated annually immediately after fruit set for all irrigated treatments when midday leaf ψ dropped below -1.0 MPa. Treatments were based on crop evapotranspiration (ET_c): non-irrigated control, PRD (100% ET_c), full irrigation (100% ET_c; hereafter 100ET) and RDI (25% ET_c). Within each treatment replicate, 10 equally-spaced vines were chosen for data collection. Irrigation was provided through a trickle system using RAM® drip-tubing (Netafim, Fresno, CA) with 1.70 L/h emitters spaced 0.6 m apart in all irrigation treatments except PRD. Drip lines in each row were suspended at 40 cm and each had its own valve that allowed control of the irrigation for each individual treatment replicate based on the calculated water needs. The PRD treatment consisted of two irrigation lines placed in parallel in the same row, each of which had its own valve at the end of the row. Drippers (1.5 L/h) were installed 1.2 m apart alternately to each other in each irrigation line (the two PRD lines thereby together had 0.6-m dripper spacing). In PRD treatments, the amount of water calculated weekly was applied only on one side of the vine. By switching weekly the drip lines along the PRD treatment row, water was applied on each side of the vine at an interval of 14 days. All the volume of water used was calculated based on the reference evapotranspiration (ET_o), using the Penman-Monteith equation (Allen *et al.*, 1998). Weather Innovations Inc. (WIN; http://www.weatherinnovations.com/) supplied daily weather information such as: temperature (mean, maximum, minimum), relative humidity (both maximum and minimum), net radiation, precipitation, and wind speed required for calculation of ET_o. Irrigation was applied weekly. To calculate the amount of water required weekly by the vine from the ET_o value, the methodology of Van der Gulik (1987) was used [described in detail therein and elsewhere (Reynolds, 2008)]. Throughout the season, crop coefficients were calculated based on the procedure of Williams and Ayars (2005).

2. Vine and soil water status

Over the growing season, biweekly observations were conducted in order to monitor vine and soil water status. Data were collected 1-2 days prior to application of the irrigation treatments. A LI-1600 steady-state porometer (LICOR, Lincoln, NE) was used each season to measure leaf transpiration rate (Ts; µg H_2O/cm^2/s) and leaf temperature. Leaf temperature data were collected using a thermocouple wire (chromel-constantan) which came in contact with the leaf surface.

Photosynthetic photon flux density (PPFD) readings were also collected by a LI-190S-1 quantum sensor installed on the porometer. Measurements were taken between 1100h and 1400h, on three recently-expanded exposed leaves (one from three different shoots) from three vines per treatment replicate of 10 previously-marked vines. Midday leaf ψ was measured between 1100h and 1400h throughout the season, using a Scholander-type pressure chamber (Soil Moisture Corp., Santa Barbara, CA). Data were recorded on three exposed leaves from the same vines used to measure Ts. Volumetric soil water content was measured for all 10 data vines in each treatment replicate with a FieldScout® 300 soil moisture meter (TDR; Spectrum Technologies, IL) using 200 mm long rods. Soil moisture was also collected in the PRD treatment replicates by a Profile Probe PR2 (Delta-T Devices Ltd, Cambridge, UK). Two access tubes were inserted in the ground ≈ 30 cm from the trunk in the middle of each treatment replicate row, with one tube on each side of the data vines. Soil moisture was measured at six depths (10, 20, 30, 40, 60 and 100 cm).

3. Yield and vine vigour components

The data vines were harvested 1-2 days before the commercial harvest date (the second or third week of September) and yield and clusters per vine were recorded. Cluster weights were calculated from these data. Before harvest, 100-berry samples were collected randomly from each data vine and stored at -25 °C until analysis. These samples were used to determine berry weight, soluble solids (°Brix), pH, and titratable acidity (TA). Berries per cluster were calculated from cluster weight and berry weight data. Shoot growth rate was recorded in 2006 and 2007 using three readings collected when shoot growth was most active (June-July). One day before the irrigation treatments were initiated, three shoots of approximately the same length from three vines were flagged. The shoots were randomly selected to avoid potential hormonal distribution effects on shoot growth rate. Overall, 27 shoots (three shoots x three vines x three replicates) per treatment were measured each growing season. Each vine was pruned to 40 nodes per vine during the dormant season (December to February), and the annual wood removed was weighed for an estimate of vine size using an electronic scale (Rapala, China).

4. Winemaking

At harvest, 30 kg of fruit per treatment replicate were transported to Brock University's winery facility. The grapes used for wine were only those from the data vines. Grapes from each treatment replicate were de-stemmed, crushed and treated with SO_2 at 20 mg/L, and then allowed 24 h skin contact at 8 °C. Each treatment replicate was pressed off individually in a basket bladder press (Enoagricola Rossi s.r.l., Calzolaro, PG, Italy) at maximum 2 bars pressure and transferred to a 20-L carboy, then sulfited to 40 mg/L. A 250-mL must sample was retained from each treatment replicate for subsequent analysis. Each treatment replicate was inoculated with Zymaflore VL3 (*Saccharomyces cerevisiae*) yeast (Lallemand Inc., Montreal, QC). The fermentations took place in a climate-controlled (16 °C) room and lasted 10-14 days. When fermentation was completed, wines were racked and sulphited to 40 mg/L. After another 10 days at -2 °C for cold stabilization, wines were racked and stored at 6 °C until bottling. All wines were bottled ≈ 3 to 4 months after fermentation. Before bottling, they were racked one more time, free SO_2 was adjusted for each wine, and filtration took place using 0.45-µm pad and 0.2-µm cartridge filters. The wines were then bottled under cork and stored at 12 °C in the CCOVI- Brock University wine cellar.

5. Berry, must, and wine composition

Berry samples were removed from the -25 °C storage, counted, weighed, placed into 250-mL beakers, and allowed to thaw. The berry and must samples were heated at 80 °C in a water bath (Fisher Scientific Isotemp 228) for one hour to dissolve precipitated tartrates. Berry samples were cooled to room temperature and juiced in a commercial fruit and vegetable juicer (Omega 500™, Denver, CO). The settled juice was centrifuged at 4500 rpm for 10 minutes in an IEC Centra CL2 (International Equipment Company, Needham Heights, MA) in order to remove any debris. The clear juice was used for soluble solids (°Brix) measurement using an Abbé refractometer (model 10450; American Optical, Buffalo, NY), pH measurement via an Accumet pH meter (model 25; Denver Instrument Company, Denver, CO), and TA with a PC-Titrate autotitrator (ManTech Associates, Guelph, ON).

Musts were analyzed for °Brix, TA, and pH, and wine samples were analyzed for TA and pH as described above. Ethanol concentration was measured in wines by gas chromatography (GC). Wine samples were filtered through a 0.45-mm Durapore membrane filters (Millipore, Ireland), and 1 mL of wine was diluted in 9 mL of distilled water. Diluted samples and nine calibration standards (% EtOH = 0.6%; 0.8%; 0.9%; 1%; 1.1%; 1.2%; 1.3%; 1.4%; 1.5%) were combined with 10 mL of 100% 1-butanol (internal standard) in 5-mL volumetric flasks. Samples and standards were analyzed on an Agilent 6890 series GC system (Agilent Technologies, Mississauga, ON) running on ChemStation software and equipped with a Supelco 24136 capillary column (Supelco Canada, Mississauga, ON). Column dimensions were 30.0 m x 0.250 mm i.d. x 0.25 mm film thickness. The carrier gas was He passed through an in-line hydrocarbon and moisture trap (Chromatographic Specialties Inc., Brockville, ON). Other conditions of operation included: oven initial temperature 60 °C, injection temperature 230 °C, detector temperature 225 °C.

6. Sensory analysis

Wines from the 2007 vintage were subjected to sensory analysis. Due to high acidity and lack of any apparent sensory differences in preliminary evaluations, the 2006 wines were excluded from sensory evaluation. Eleven volunteer judges from 23 to 58 years of age and with previous sensory training were involved over the 3-month period. The group was composed of Brock University faculty, staff, and students from the viticulture and oenology program, and were selected based on availability and motivation.

Discrimination test. A modified alternative forced choice test (5-AFC) was used to compare a control wine (non-irrigated) to each irrigation treatment to find differences between control and all others (O'Mahony, 1986). This was intended as a preliminary exercise to determine whether differences exist between treatments, what the basis for those differences might be, and whether the panellists were dependable. The test ran over 3 weeks, testing three field replicates. One field replicate was assessed weekly. Each flight had five wines. Two control (non-irrigated) wine samples were included in each flight replicate.

Descriptive analysis. Six training sessions were run over a period of 3 weeks. Samples used for training purposes came from two of the field replicates. In each session, they tested four wines (non-irrigated, 100ET, PRD and RDI). Panellists were asked to note flavour or aroma attributes that could describe the variability among the wines. The descriptor list was adjusted until all panellists agreed with the definitions. Reference standards were created to help panellists define and rate each attribute (Table 1). References were adjusted during the training sessions until everyone agreed that the reference was representative of that particular attribute (Table 1). Aroma standards were prepared in 100 mL base white wine. The base wine was a neutral white blend (table wine) from Kressmann Winery, Bordeaux, France. After the first two sessions, the panellists were asked to compare all the wines with the control for each attribute collected. A two-way unstructured scale was selected and verbal descriptions at the end points were used to collect sensory data. The control wine (non-irrigated) was anchored in the middle of the 15-cm scale. The ends of the scale were anchored with verbal descriptions: left (lowest) and right (highest). In each session, the control wine was assessed for each attribute. Panellists were instructed in the use of the line scale to aid in improving reliability and reproducibility in assessing attribute intensity. During the training session the panellists were asked to rate each coded wine on the left side of the scale if the intensity was lower than the control (non-irrigated) or on right side if it was higher than the control.

Sensory data collection. Data collection took place in the sensory laboratory at CCOVI (Brock University) using a computerized sensory software program (Compusense c5v4, Guelph, ON). Samples were evaluated in individual sensory booths using ISO glasses, and under red light to mask wine hue. Wines were assessed in four replicates (sessions). In each session, all four wines were evaluated in a randomized order according to the Williams block design. Each session had three flights. Panellists rated the samples based on the list of attributes on a two-way unstructured scale. To rest the palate and avoid any bias, a 1-minute rest between each sample and a 5-minute rest after each group of wines was included. Evaluations started at 1100 h and continued to 1300 h. All wines were presented as 25-mL samples coded with a three-digit random number. Each glass was covered with a Petri dish to prevent volatile loss. Aroma standards developed during the training sessions were prepared fresh daily and available for judges as reference prior each session. The sensory

Table 1. Attributes and their standard references used for sensory evaluation of Sauvignon blanc wines, 2007.

Sensory attribute	Reference standard (prepared in 100 mL base white wine Kressmann – Bordeaux, France)
Honey	1 mL of buckwheat honey
Tropical fruit	Two pieces of fresh passion fruit and grapefruit (≈ 15 g)
Boxwood	Ten crushed leaves of boxwood
Melon	Honeydew melon (20-25 g)
Hay	5 g of hay
Stone fruit	10 mL (apricot and peach canned) – No Name brand (No Frills)
Lemon grass	5 g of lemon grass leaves
Acidity	1.5 g tartaric acid/L water

data were analyzed for significance using the real values (positive or negative values compared to control). To depict the sensory profile of the control and all irrigation treatments on cobweb plots, the mean intensity score for each attribute (irrigation sample) was subtracted or added to the corresponding descriptor score of the control wine (non-irrigated). A blind control was assessed during these sessions for all the sensory descriptors to generate values for the non-irrigated treatment for the cobweb plots.

7. Data analysis

Field data (leaf ψ, Ts, soil moisture), berry, and wine chemical data were analyzed using SAS statistical package (SAS Institute; Cary, NC). Using the General Linear Models Procedure, analysis of variance was performed on physiological and chemical data. Duncan's multiple range test was used for means separation for all data (field, chemical, and sensory), and Dunnett's *t*-test was used to determine those treatment means that were different from the control at a significance level of $\alpha \leq 0.05$. Sensory data were analyzed using XLSTAT (Addinsoft, Paris, France). Principal components analysis (PCA) was performed on the means of field data, chemical data, and sensory scores of aroma and flavour descriptors for each year of the experiment. Partial least squares regression (PLS) was performed on the field, chemical and sensory data to find relationships among these data.

RESULTS

1. General meteorology

The 2006 and 2008 years had wet growing seasons with a total rainfall of 220 and 345 mm, respectively, from June to August. The 2007 season was the driest with a total rainfall of only 56 mm in the June to August period, which was approximately 25% of that in 2006. In 2007, particularly in May and July, temperatures were also considerably higher (2.5-3 ^{o}C) than average.

2. Soil moisture

TDR measurement. Soil moisture measured by TDR had a different trend each year. A clear separation among the treatments was observed at beginning of July and August 2006 with PRD and 100ET most effective in increasing soil water content (Figure 1A). However, on 2 August, soil moisture in the PRD treatment was higher than the others. The lowest soil moisture values were below wilting point (13.3%; Kingston and Presant 1989), likewise found on 2 August in all treatments except the PRD. This period (late July/early August) was characterized by a

Table 2. Impact of irrigation strategies on soil moisture (% volumetric content) of Sauvignon blanc measured using a TDR at 200 mm depth, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006 and 2007

		2006					
	Side	21-Jun	04-Jul	18-Jul	01-Aug	15-Aug	30-Aug
C		16.0b	14.8b	18.9b	9.8c	16.1b	15.4c
PRD	Wet	19.6a	20.6a	21.4a	21.5a	22.3a	18.5b
	Dry	16.2b	12.3c	17.3c	15.8b	16.2b	14.8c
Full		16.2b	16.1b	19.2b	11.8bc	22.1a	22.6a
RDI		15.1b	12.1c	19.0b	10.5c	15.4b	17.6b
Significance		**	***	*	***	**	**
		2007					
Treatment	Side	27-Jun	11-Jul	25-Jul	08-Aug	21-Aug	
C		15.5b	13.9b	12.1b	13.5b	11.5b	
PRD	Wet	15.2b	19.1a	20.1a	19.1a	18.2a	
	Dry	14.6b	11.1c	12.3b	13.1b	12.1b	
Full		18.1a	19.5a	20.5a	18.8a	17.5a	
RDI		15.2b	13.2b	12.3b	13.1b	12.6b	
Significance		**	***	***	***	**	

C-control (non-irrigated), PRD-partial root zone drying (100% ETc), Full (100ET), and RDI-regulated deficit irrigation (25% ETc). *, **, ***, ****, ns: significant at $p < 0.05$, 0.01, 0.001, 0.0001, or not significant, respectively. Letters within columns represent means separated at $p < 0.05$, Duncan's multiple range test.

lack of precipitation, high temperatures and high solar radiation. Trends were similar in 2007 for PRD and 100ET treatments, albeit with slightly higher values at the end of July compared to the rest of the season (Figure 1B). Soil moisture in non-irrigated and RDI treatments was consistently lower than the PRD and 100ET treatments. However, soil moisture in the PRD treatment was lower than the 100ET treatment and higher than the non-irrigated and RDI vines. In 2007, soil moisture was different among treatments throughout the season. In 2008, soil moisture followed the same trend as precipitation, with a maximum at the end of July corresponding to the maximum amount of precipitation (Figure 1C). Soil moisture pattern was different than in the previous two seasons. Soil moisture did not drop below wilting point in 2008 at any sampling date. Soil moisture data indicated significant variation among treatments when the two sides (wet and dry) of the PRD treatment were considered (Table 2). There was consistently higher moisture in the PRD treatment (wet side) than in the 100ET treatment. This could be explained by the fact that in the PRD treatments, the same amount of water was delivered as in the 100ET treatment, but only on one side of the vine. Also, through alternation of irrigation in the PRD treatment, the dry side had lower soil moisture values compared to the control.

Profile Probe. Despite occasional rainfall and clay-based soil that permits horizontal water movement through capillarity, soil moisture measured by the Profile Probe in the PRD treatment clearly showed differences between dry and wet sides on most sampling dates in 2006 and 2007 (Table 3). Due to consistently high soil moisture in 2008, data are not shown. The soil moisture showed a maximum difference of 20% between wet and dry sides in 2006 while in 2007 the difference between wet and dry was almost 50%. Soil moisture varied in both years in PRD treatments not only between wet and dry zones but also with depth. In 2006, the differences between wet and dry zones on the first sampling date were low at all depths. The soil moisture at any given depth did not show high fluctuations over the season in either the wet or dry zones. At the 30 cm depth, soil moisture was much lower in the dry zone compared to the other depths. Overall, in 2007, soil moisture had lower values in both zones compared to those found in 2006. The lowest difference between dry and wet zone was recorded at the 100 cm depth. Moreover, the soil moisture at the same depth was consistently higher than that found at the other depths. However, the 2006 and 2008 seasons were wetter than normal, and excess rainfall made it difficult to achieve clear separation among treatments.

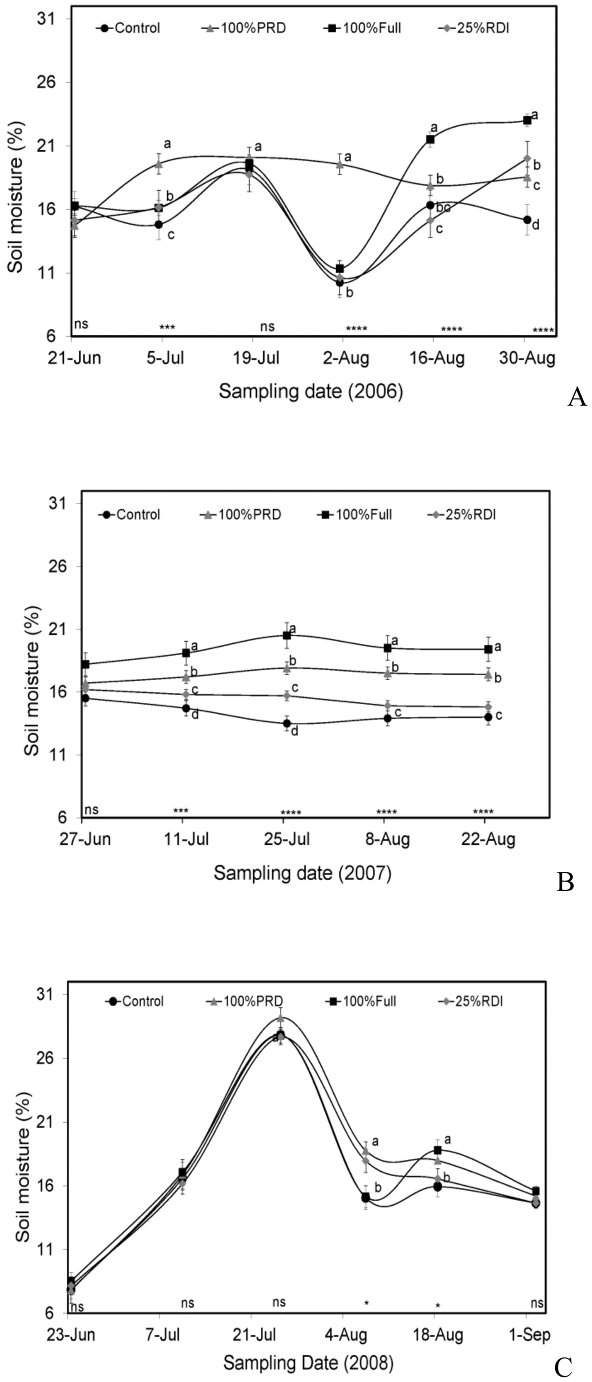

Figure 1. Impact of irrigation treatments on soil moisture (%) of Sauvignon blanc vines measured by FieldScout 300 TDR at 200 mm depth, Lambert Vineyards, Niagara-on-the-Lake, ON. A: 2006; B: 2007; C: 2008. Control (non-irrigated), PRD-partial root zone drying (100% ET_c), Full (100ET), and RDI-regulated deficit irrigation (25% ET_c). 100 and 25% represent percentage of water replaced through irrigation. ET_c-crop evapotranspiration. *, **, *, ****, ns: significant at $p \leq 0.05$, 0.01, 0.001, 0.0001, or not significant, respectively. Letters represent means separated at $p \leq 0.05$, Duncan's multiple range test.**

3. Vine water status

Transpiration. In 2006, all treatments followed a decreasing trend in Ts between the beginning of July and late August (Figure 2A). Despite the fact that the same amount of water was applied in the PRD treatment as the 100ET treatment, Ts values were close to the control in the PRD treatment. As expected, the Ts rate was lower in PRD than in the 100ET treatment. However, PRD closely followed the non-irrigated and RDI treatments in August. In 2007, Ts was much lower than in 2006, and responded better to irrigation treatments (Figure 2B). The trend in Ts rate was downward until the beginning of July. Afterwards, the Ts values showed a steady trend throughout the season. However, the highest magnitude of difference was between 100ET treatment and the other treatments. In 2008, contrary to expectations, the Ts trend was very different from previous years (Figure 2C). Despite high soil moisture throughout the season, Ts showed a steady downward trend in all treatments, having similar values to those from 2007. The lowest values were recorded in the first week of July. Small differences between treatments appeared at the end of July, even though no irrigation treatments had been applied up to that point. Due to high precipitation in 2008, irrigation treatments were applied only in the last 3 weeks of August, coinciding with veraison. The average values for Ts in 2008 were less than the values of 2006 and 2007 despite higher soil moisture, which can be explained by lower temperature and solar intensity, two major factors that drive vine transpiration.

Leaf water potential. Leaf ψ had a different pattern in each year of the study. In 2006, leaf ψ showed a different trend than that one found in Ts (Figure 3A). PRD and 100ET treatments had the highest leaf ψ while non-irrigated and RDI treatments had much lower values. The highest magnitude of difference among treatments was recorded at beginning of August, during which the leaf ψ varied from -0.78 MPa in 100ET treatment to -1.14 MPa in the non-irrigated treatment. The greatest separation of treatments based on leaf ψ occurred in 2007 (Figure 3B). Leaf ψ reached the minimum value (-1.4 MPa) in the non-irrigated treatment, at the end of August. The PRD treatment displayed lower water status than the 100ET treatment on all sampling dates but much higher than the control and 25% ET_c RDI. The leaf ψ values were > -1.0 MPa in PRD and 100ET treatments throughout the season. This suggests that vines under these two treatments did not experience water stress, since -1.0 MPa is considered as the threshold point for white varieties at which vines can begin to suffer from water stress (Goldammer, 2013).

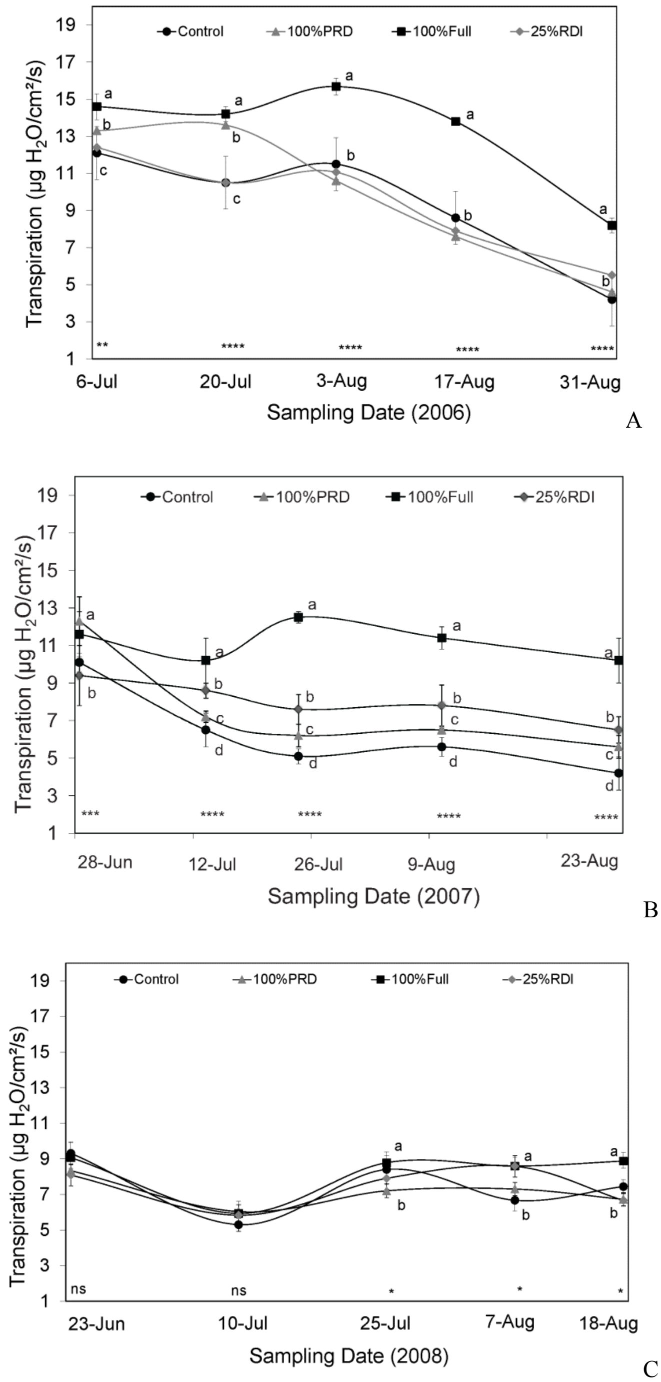

Figure 2. Impact of irrigation treatments on transpiration of Sauvignon blanc vines, Lambert Vineyards, Niagara-on-the-Lake, ON. A: 2006; B: 2007; C: 2008. Control (non-irrigated), PRD-partial root zone drying (100% ETc), Full (100ET), and RDI-Regulated deficit irrigation (25% ETc). 100 and 25% represent percentage of water replaced through irrigation. ETc-crop evapotranspiration. *, **, *, ****, ns: significant at p ≤ 0.05, 0.01, 0.001, 0.0001, or not significant, respectively. Letters represent means separated at p ≤ 0.05, Duncan's multiple range test.**

Table 3. Impact of PRD irrigation treatments on soil moisture (% volumetric content; with associated p-values) of Sauvignon blanc measured using a Profile Probe type PR2™ at six depths, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006 and 2007. Each value is a mean of four PRD replicate readings. "Wet" and "Dry" are the irrigated and non-irrigated sides in the row from one vine of the PRD treatment.

Sampling date	Sampling Depth											
	10 cm		20 cm		30 cm		40 cm		60 cm		100 cm	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
2006												
21-Jun	15.1	16.2	19.6	16.2	13.6	12.8	21.2	21.5	16.2	14.9	21.5	19.5
	0.560		*0.222*		*0.574*		*0.920*		*0.223*		*0.219*	
4-Jul	20.6	12.3	20.6	15.2	21.3	13.8	20.6	18.1	17.3	12.1	21.9	17.2
	0.003		*0.030*		*0.024*		*0.096*		*0.001*		*0.048*	
18-Jul	18.6	17.5	21.4	17.3	18.9	13.1	18.6	16.9	16.8	11.4	18.9	16.1
	0.225		*0.009*		*0.004*		*0.092*		*0.010*		*0.003*	
1-Aug	19.8	11.3	21.5	15.8	19.1	13.4	19.8	14.3	17.9	11.5	18.1	13.2
	0.001		*0.017*		*0.008*		*0.008*		*0.002*		*0.034*	
15-Aug	17.2	12.5	22.3	16.2	18.9	12.9	17.2	15.1	18.1	10.9	18.9	13.8
	0.007		*0.021*		*0.005*		*0.079*		*0.001*		*0.014*	
30-Aug	18.9	11.6	18.9	11.6	17.5	11.1	18.9	14.9	17.6	12.6	17.6	14.2
	0.001		*0.001*		*0.007*		*0.007*		*0.003*		*0.020*	
2007												
27-Jun	18.1	15.1	15.2	14.6	13.8	15.2	17.5	16.2	18.2	13.6	19.9	17.9
	0.001		*0.699*		*0.523*		*0.641*		*0.004*		*0.121*	
1-Jul	19.6	9.2	19.1	11.1	21.9	13.2	19.2	12.9	19.1	14.2	20.6	16.8
	0.0001		*0.001*		*0.002*		*0.004*		*0.007*		*0.090*	
25-Jul	21.1	10.1	20.1	12.3	19.2	12.9	19.5	11.8	17.6	13.9	19.2	17.9
	0.001		*0.006*		*0.039*		*0.001*		*0.042*		*0.468*	
8-Aug	19.6	11.5	19.1	13.1	18.6	11.3	18.9	12.3	17.2	12.8	19.8	16.5
	0.007		*0.034*		*0.012*		*0.006*		*0.026*		*0.046*	
21-Aug	19.1	10.6	18.3	12.9	17.9	12.5	17.6	11.6	18.3	13.4	18.3	12.1
	0.001		*0.001*		*0.018*		*0.049*		*0.029*		*0.037*	

*numbers in italics represent the p values

In 2008, leaf ψ had the lowest values in the first week of July, when all treatments fell to < -1.0 MPa (Figure 3C). High precipitation thereafter alleviated water stress during the season, and the leaf ψ values were between -0.8 and -0.9 MPa.

4. Shoot growth and vine size

In 2006, vine size was highest in 100ET and RDI treatments (Table 4). The PRD treatment, which also received 100% ET_c, had a lower vine size than the RDI vines. In 2006, shoot growth rate showed an increasing trend in 100ET treatment with a maximum in the first week of July (Figure 4A). The greatest magnitude of difference among treatments was found at the beginning of July with values between 5 and 43 cm. Even in a wet year such as 2006, shoot growth rate showed a steadily decreasing trend, reaching a minimum at the end of July. The 100ET treatment had the highest shoot growth rate in both 2006 and 2007. Shoot growth in 2006 was more advanced at the time that data collection began compared to 2007. In 2007, vine size was highest in 100ET, while vine size in the PRD treatment did not differ from non-irrigated vines. The maximum growth rate was reached almost one week later in 2007 compared to 2006 (Figure 4B). This can be explained by higher precipitation in 2006 that accelerated shoot growth in all treatments. PRD vines had a shoot growth rate intermediate between that of the control and 100ET treatments. In 2008, vine size was not different among treatments, which is unsurprising considering the consistently high soil moisture throughout the season (Table 4). In 2008,

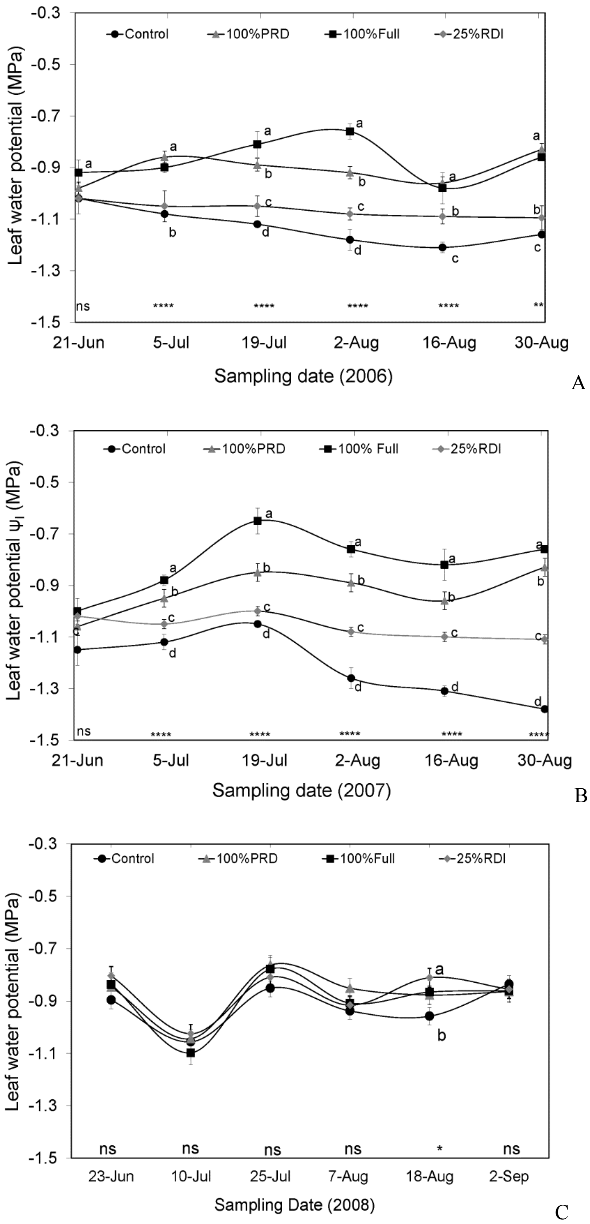

Figure 3 - Impact of irrigation treatments on leaf water potential of Sauvignon blanc vines, Lambert Vineyards, Niagara-on-the-Lake, ON. A: 2006; B: 2007; C: 2008. Control (non-irrigated), PRD-partial root zone drying (100% ET_c), Full (100ET), and RDI-regulated deficit irrigation (25% ET_c). 100 and 25% represent percentage of water replaced through irrigation. ET_c-crop evapotranspiration. *, **, ***, ****, ns: significant at $p \leq 0.05$, 0.01, 0.001, 0.0001, or not significant, respectively. Letters represent means separated at $p < 0.05$, Duncan's multiple range test.

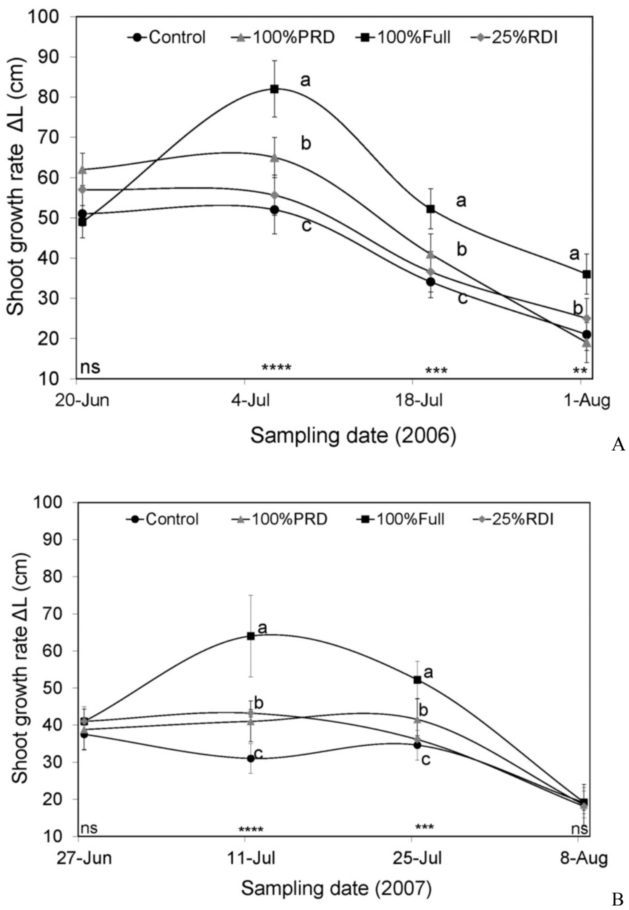

Figure 4 - Impact of irrigation treatments on shoot growth rate (cm) of Sauvignon blanc vines, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006 (A) and 2007 (B). Control (non-irrigated), PRD-partial root zone drying (100% ET_c), Full (100ET), and RDI-regulated deficit irrigation (25% ET_c). 100 and 25% represent percentage of water replaced through irrigation. ET_c-crop evapotranspiration. *, **, *, ****, ns: significant at $p \leq 0.05$, 0.01, 0.001, 0.0001, or not significant, respectively. Letters represent means separated at $p \leq 0.05$, Duncan's multiple range test.**

shoot growth data were collected just once, and due to high precipitation, no treatment differences occurred (data not shown).

5. Yield components

Few yield variables were affected by irrigation in 2006. There were no yield differences between non-irrigated and other treatments, although RDI and PRD had yields slightly lower than the control (Table 4). The PRD and 100ET treatments had lower clusters per vine. This variation is not well explained by the treatments since cluster differentiation occurred in the previous year when no treatments were applied. However, the 100ET treatment was different than the control in terms of cluster weight and berry weight. Surprisingly, although PRD received 100% ET_c replacement, it was different only in terms of berry weight (Table 4). In 2007, yield components responded better to irrigation treatments. Yield was highest in 100ET vines and was different from non-irrigated, while PRD and RDI were slightly higher than the non-irrigated vines. Contrary to 2006, in 2007 the highest number of clusters per vine was found in the RDI treatment, while PRD and 100ET treatments showed intermediate values. This situation occurred due to the irrigation treatments initiated in 2006, or due to the climatic conditions during the previous season. However, the cluster and berry weights had the highest values in 100ET vines. The clusters per vine in the PRD treatment were not different compared to control, although they were 10% heavier (Table 4). In 2008, the PRD treatment had the lowest yield, mainly due to the lowest clusters per vine. However, no differences were observed among treatments in terms of cluster weight and berries per cluster (Table 4). In 2008, yield components had higher values in all treatments compared with 2006 and 2007.

6. Berry composition

All constituents were affected by the irrigation treatments. In 2006, 100ET and RDI treatments had higher °Brix than PRD and non-irrigated treatments, contrary to expectations, while TA was higher in all irrigated treatments compared to the control (Table 5). Berry pH was higher than non-irrigated only in PRD and 100ET treatments. °Brix values were much lower in 2007 compared to 2006 and 2008 seasons (Table 5). However, the 100ET treatment had the lowest °Brix while PRD had the highest °Brix. Berry TA was the lowest in the control. TA values were higher in RDI than PRD, although more water was applied in the PRD. All irrigated treatments displayed small increases in berry TA, but only the 100ET displayed other differences relative to the control (lower °Brix, higher pH). In 2008, there were no differences in °Brix among treatments but they had overall slightly higher values than in 2007. However, in 2008 TA had higher values in PRD and 100ET, while pH was higher in non-irrigated and PRD treatments.

7. Must and wine composition

In 2006, the highest must °Brix was found in the PRD treatment and the lowest in the 100ET (Table 5). This pattern was different than that found for berry

Table 4. Impact of irrigation treatments on yield components and vine size of Sauvignon blanc, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006-2008

Treatment	Vine size (kg/vine)	Yield (kg/vine)	Clusters/vine	Cluster wt. (g)	Berries/cluster	Berry wt. (g)
			2006			
C	0.71 b	7.95 ab	65 a	121.0 b	89 ab	1.38 b
PRD	0.69 b	7.44 b	59 b	121.6 b	84 b	**1.46 a**
Full	**0.86 a**	8.16 a	59 b	**136.3 a**	93 a	**1.49 a**
RDI	**0.84 a**	7.88 ab	62 ab	126.7 ab	85 b	**1.47 a**
Significance	*	*	*	*	*	**
			2007			
C	0.60 b	6.45 b	53 b	123.2 b	88	1.41 b
PRD	0.61 b	7.97 ab	60 ab	136.3 ab	91	1.47 b
Full	**0.76 a**	**8.61 a**	59 ab	**152.6 a**	92	**1.67 a**
RDI	0.65 ab	8.12 ab	**65 a**	127.4 b	90	1.41 b
Significance	**	**	*	***	ns	***
			2008			
C	0.86	10.03 b	61 b	164.4	85	1.93 b
PRD	0.87	9.40 c	56 c	167.8	83	**1.99 a**
Full	0.91	**11.78 a**	**70 a**	168.2	86	**1.98 a**
RDI	0.87	11.36 ab	67 ab	169.5	84	1.94 b
Significance	ns	*	*	ns	ns	*

C-control (non-irrigated), PRD-partial root zone drying (100% ETc), Full (100ET), and RDI-regulated deficit irrigation (25% ETc). *, **, ***, ****, ns: significant at $p < 0.05$, 0.01, 0.001, 0.0001, or not significant, respectively. Letters within columns represent means separated at $p < 0.05$, Duncan's multiple range test. Boldfaced data indicate those values significantly greater than the control using Dunnett's t-test; underlined data are significantly less than the control.

Table 5 - Impact of irrigation treatments on berry, must, and wine composition of Sauvignon blanc, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006-2008

Treatment	°Brix		EtOH	Titratable acidity (g/L)			pH		
	Berries	Must	Wine	Berries	Must	Wine	Berries	Must	Wine
2006									
C	19.5 b	18.2 b	10.12 ab	9.1 c	8.3 b	5.6 b	3.49 b	3.46 b	3.51 b
PRD	19.6 b	**19.2 a**	10.45 a	**9.4 b**	9.0 ab	6.0 ab	**3.56 a**	3.56 ab	3.53 ab
Full	**20.2 a**	<u>17.6 c</u>	9.63 b	**9.6 a**	**9.3 a**	**6.2 a**	**3.57 a**	**3.60 a**	**3.59 a**
RDI	**20.3 a**	18.9 ab	9.88 ab	**9.3 b**	9.0 ab	5.8 ab	3.53 ab	<u>3.36 c</u>	<u>3.38 c</u>
Significance	*	*	*	***	***	***	*	**	**
2007									
C	18.3 ab	17.6 ab	9.65 b	6.8 b	7.9 b	5.0 c	3.54 b	3.23 b	3.26 b
PRD	18.9 a	17.8 a	**9.78 a**	7.2 ab	<u>7.6 c</u>	5.2 c	3.58 ab	3.26 ab	3.26 b
Full	<u>17.6 c</u>	<u>16.8 c</u>	<u>9.17 c</u>	**7.5 a**	**8.5 a**	**5.8 a**	**3.63 a**	3.25 ab	3.25 b
RDI	18.1 b	17.1 b	9.50 bc	**7.4 a**	8.0 b	**5.5 b**	3.57 ab	**3.29 a**	**3.29 a**
Significance	*	*	*	***	***	****	***	***	***
2008									
C	19.7			7.8 b			3.65 a		
PRD	19.6			**8.2 a**			3.66 a		
Full	19.6			**8.3 a**			<u>3.60 b</u>		
RDI	19.9			7.9 b			<u>3.59 b</u>		
Significance	ns			*			*		

C-control (non-irrigated), PRD-partial root zone drying (100% ET_c), Full (100ET), and RDI-regulated deficit irrigation (25% ET_c). 100 and 25% represent percentage of water replaced through irrigation. ET_c-crop evapotranspiration. *, **, ***, ****, ns: significant at $p < 0.05$, 0.01, 0.001, 0.0001, or not significant, respectively. Letters within columns represent means separated at $p < 0.05$, Duncan's multiple range test. Boldfaced data indicate those values significantly greater than the control using Dunnett's t-test; underlined data are significantly less than the control.

Table 6 - Comparison of mean sensory scores among the irrigation treatments of Sauvignon blanc wines, Lambert Vineyards, Niagara-on-the-Lake, ON, 2007

Variable/Treatment	C	PRD	Full	RDI	Pr>F
Aroma					
Honey	2.3 c	4.1 a	2.6 c	3.3 b	<0.001
Tropical fruit	1.8 c	2.1 c	2.9 b	3.5 a	0.028
Boxwood	2.1 c	2.7 ab	2.9 a	2.5 b	0.009
Melon	3.2 b	3.7 a	2.9 b	3.6 ab	0.016
Hay	1.8 c	2.3 b	1.7 c	2.9 a	0.006
Stone fruit	2.1 c	2.8 ab	2.6 b	3.6 a	0.009
Lemon grass	1.4 c	2.3 b	2.9 ab	3.2 a	0.005
Flavour/mouthfeel					
Honey	3.1 a	2.1 b	2.3 b	2.9 ab	0.008
Tropical fruit	2.1 b	1.8 b	1.8 b	3.1 a	0.021
Boxwood	2.3 bc	2.1 c	3.1 a	2.8 b	0.034
Melon	2.9 b	3.6 a	2.8 b	3.2 ab	0.038
Hay	1.5 c	2.5 b	3.8 a	2.9 b	0.007
Stone fruit	2.9 ab	3.1 a	1.1 c	2.6 b	<0.001
Lemon grass	2.1 c	3.4 b	3.1 b	3.8 a	0.006
Acidity	1.5 c	3.1 ab	3.6 a	2.7 b	0.001

C-control (non-irrigated), PRD-partial root zone drying (100% ETc), Full (100ET), and RDI-regulated deficit irrigation (25% ETc). ETc-crop evapotranspiration. Means within rows with different letters are significantly different, Duncan's multiple range test.

composition. Must pH was highest in the fully irrigated treatment and lowest in the RDI treatment. One interesting observation was that must from PRD and RDI treatments had the same TA but different pH values. The pH was much lower in the RDI. In 2007, contrary to expectations, must °Brix was much lower in all treatments than in 2006. The lowest °Brix was found in the 100ET treatment. Moreover, pH values were much lower in all treatments compared to 2006. Wine ethanol concentration followed the same pattern as °Brix in the corresponding must in 2006. Wine TA decreased in all treatments following the same pattern as in the musts. Wine pH showed a slightly decreasing trend in all wines (Table 5). In 2007, all the wines had lower ethanol concentration compared to those from 2006. The difference among treatments was slightly lower in 2007 than in 2006. The pH in 2007 was not different in any wine from that found in the corresponding must.

8. Sensory analysis

The 2007 vintage was assessed for seven aroma and eight flavour and mouthfeel descriptors. Substantial differences occurred between the control and the irrigated treatments. The PRD wines, despite having higher intensities of some aroma and flavour descriptors compared to the control, were not different from the 100ET or RDI treatments. RDI wines showed the greatest difference from the control for all descriptors except honey and melon flavour (Table 6). Honey and melon aroma were highest in PRD wines. The control showed the highest intensity of the honey descriptor, although the score for stone fruit was very close to that from PRD. The PRD wines had highest scores for melon and stone fruit. Lemon grass and acidity were higher in irrigated treatments compared to the control. Overall, RDI showed higher intensities for most of the typical descriptors for this cultivar. However, boxwood and hay are common descriptors for Sauvignon blanc wines from cool regions. These two descriptors, which generally describe the "green" character of Sauvignon blanc, had higher scores in irrigated treatments compared to the control (Table 6). By plotting mean sensory scores on radar diagrams for each treatment, data clearly showed that not only the water status affected the wine sensory profile but also the irrigation strategy used (Figure 5).

The PCA on 2007 sensory data showed that the first two factors explained 78.6% of variability (Figure 6). PC1 explained 44.9% while PC2 explained 33.8% of the variability in the data set. PC1 was positively loaded with lemon grass, tropical fruit, boxwood aroma and acidity, and negatively loaded with honey aroma. PC2 was positively loaded with melon aroma and flavour. The distribution of 2007 wines on the PCA plot showed a good discrimination among the treatments. Contrary to expectations, PRD (100% ET_c) located in the upper right plane and the 100ET treatment located in the lower right plane, and therefore they were not associated with the same aroma and flavour descriptors. The PRD and RDI treatments were located in the same plane, being associated with stone fruit, tropical fruit, honey, and melon descriptors.

9. Relationships among soil and plant water status, yield components and chemical data

2006. PLS performed on soil and vine water status, yield components and berry composition data illustrated a high degree of correlation between Ts rate, leaf ψ and juice pH (Figure 7). This suggests that Ts rate might be a good predictor for juice pH. However, this is not the case all the time since it is well known that under particular climatic condition both Ts rate and leaf ψ could be affected by factors other than soil moisture. All these variables were negatively correlated with leaf temperature. Leaf temperature increases when the Ts rate is low, and conversely a high Ts rate should be expected under conditions of consistently high soil moisture. Vine size was highly positively correlated with °Brix and TA in berry and wine and negatively correlated with ethanol concentration. These relationships indicate that irrigation treatments that control canopy size did not have a negative effect on °Brix accumulation. Although soil moisture might increase the vine canopy density, an appropriate balance between total leaf area and crop load would not negatively affect berry sugar accumulation. Yield was highly positively correlated with berries per cluster, and negatively correlated with wine pH. This relationship could not be explained by the treatments since flower differentiation occurs at budburst or immediately afterwards.

2007. The PCA plot of field data indicated that F1 and F2 explained 99.97% of the total variability in the data set (Figure 8). This shows that in very hot and dry seasons, in areas normally considered cool, soil and plant water status variables react differently to the strategy and volume of water applied through irrigation. Soil moisture was highly positively correlated with leaf ψ, and negatively correlated with leaf temperature. Despite the fact that leaf ψ is affected more by the vapour pressure deficit and less by the soil moisture, the data indicated a good correlation between ψ and soil moisture. Vine size did not explain the variability in F1 and F2. All four irrigation treatments were well separated by their

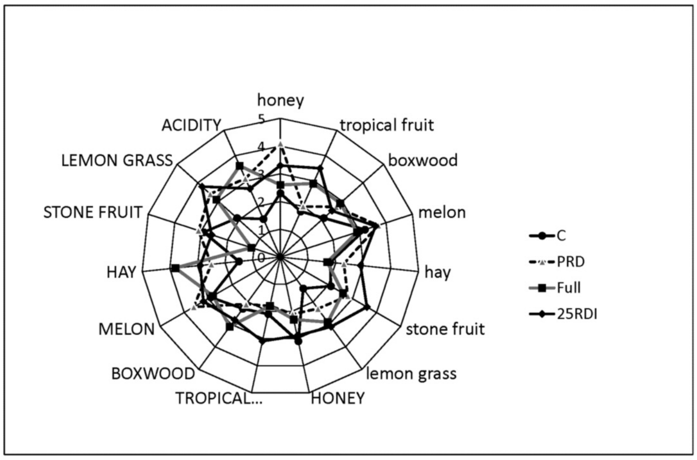

Figure 5 - Radar diagram of the mean intensity ratings of 11 trained panellists for four Sauvignon blanc wines made from different irrigation treatments, Lambert Vineyards, Niagara-on-the-Lake, ON, 2007. Aroma and flavour attributes are specified by lower and higher case letters, respectively. C-control (non-irrigated), PRD-partial root zone drying (100% ET_c), Full (100ET), and RDI-regulated deficit irrigation (25% ET_c). 100 and 25% represent percentage of water replaced through irrigation. ETc-crop evapotranspiration.

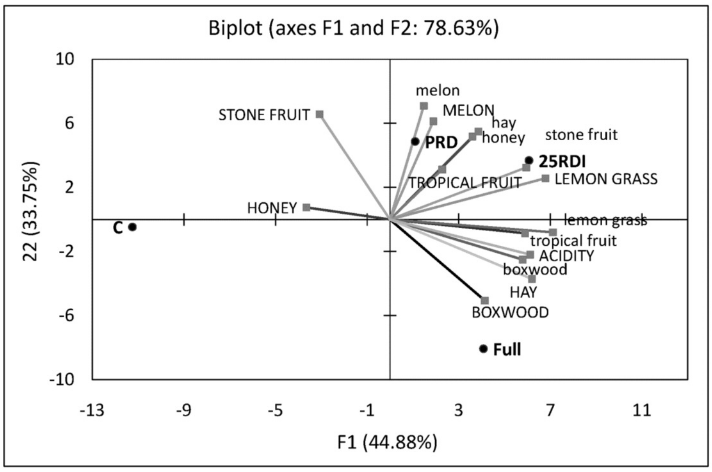

Figure 6 - Principal component analysis (F1 and F2) of mean sensory data for wines made from four irrigation treatments of Sauvignon blanc from Lambert Vineyards, Niagara-on-the-Lake, ON, 2007. C-control (non-irrigated), PRD-partial root zone drying (100% ET_c), Full (100ET), and RDI-regulated deficit irrigation (25% ET_c). 100 and 25% represent percentage of water replaced through irrigation. ETc-crop evapotranspiration.

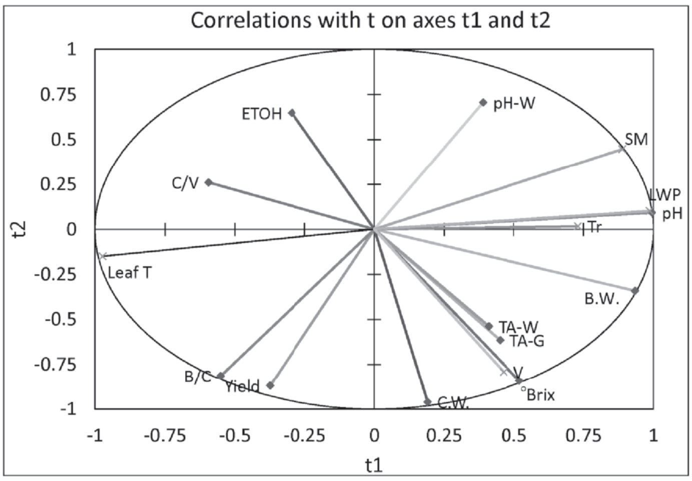

Figure 7 - PLS analysis of soil and vine water status, yield components, berry and wine chemical composition means from four irrigation treatments of Sauvignon blanc from Lambert Vineyards, Niagara-on-the-Lake, ON, 2006. Abbreviations: SM-soil moisture; Leaf T-leaf temperature; LWP-leaf water potential; Ts-transpiration; V-vine size; C/V-clusters per vine; C.W.-cluster weight; B/C-berries per cluster; B.W.-berry weight; TA-W-wine titratable acidity; TA-G-berry titratable acidity; ETOH-ethanol content; pH-W-wine pH.

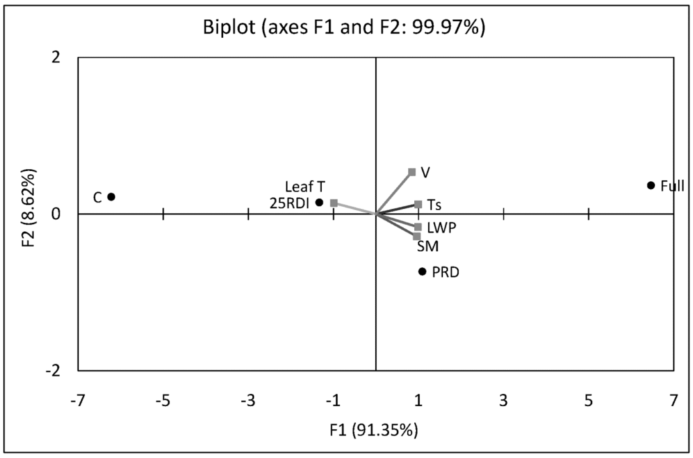

Figure 8 - Principal component analysis (F1 and F2) of soil water status and physiological data from four irrigation treatments of Sauvignon blanc from Lambert Vineyards, Niagara-on-the-Lake, ON, 2007. C-control (non-irrigated), PRD-partial root zone drying (100% ET_c), Full (100ET), and RDI-regulated deficit irrigation (25% ET_c). 100 and 25% represent percentage of water replaced through irrigation. ETc-crop evapotranspiration. Abbreviations: SM-soil moisture; Leaf T-leaf temperature; LWP-leaf water potential; Ts-transpiration; V-vine size.

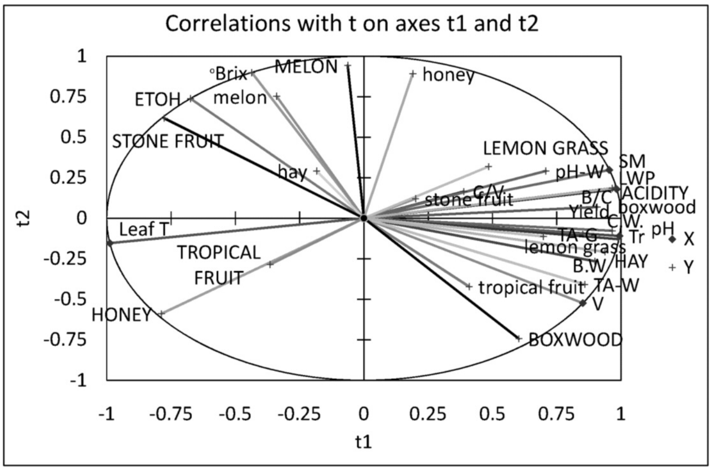

Figure 9 - PLS regression analysis of soil and plant water status, yield components, berry and wine composition and sensory data from four irrigation treatments of Sauvignon blanc from Lambert Vineyards, Niagara-on-the-Lake, ON, 2007. Abbreviations: SM-soil moisture; Leaf T-leaf temperature; LWP-leaf water potential; Ts-transpiration; V-vine size; C/V-clusters per vine; C.W.-cluster weight; B/C-berries per cluster; B.W.-berry weight; TA-W-wine titratable acidity; TA-G-berry titratable acidity; ETOH-ethanol content; pH-W-wine pH.

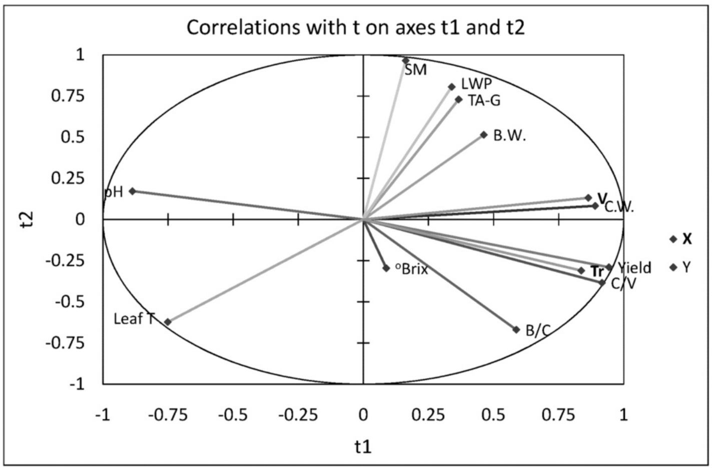

Figure 10 - PLS regression analysis of soil and plant water status, yield components and berry composition from four irrigation treatments of Sauvignon blanc from Lambert Vineyards, Niagara-on-the-Lake, ON, 2008. Abbreviations: SM-soil moisture; Leaf T-leaf temperature; LWP-leaf water potential; Ts-transpiration; V-vine size; C/V-clusters per vine; C.W.-cluster weight; B/C-berries per cluster; B.W.-berry weight; TA-G-berry titratable acidity;

effects on physiological variables. The 100ET treatment was located in the upper right plane, PRD in the lower right plane, and the control and RDI treatment were located in the upper left plane. PLS illustrated strong negative correlations between leaf temperature vs. Ts rate, leaf ψ, soil moisture, yield, clusters per vine and boxwood aroma (Figure 9). This suggests that leaf temperature could be a good predictor for soil water status and yield components. The 2007 season was characterized by high temperature and low precipitation, and the vines conserved water by stomatal closure. This could have led to overheating the leaves and inhibiting enzymatic activity. Lemon grass was strongly negatively correlated with honey and tropical fruit aroma descriptors. Soluble solids concentration was highly positively correlated with ethanol concentration, stone fruit flavour and melon aroma, and negatively correlated with tropical fruit aroma and boxwood flavour.

2008. In 2008, PLS analysis performed on field, yield components and berry composition data showed different relationships among the variables (Figure 10). Leaf temperature was highly negatively correlated with leaf ψ, berry TA, berry weight and soil moisture. Low leaf temperature indicates that soil had enough water reserves, and minimal water was lost though transpiration. Therefore, high canopy size develops, which in turn extends the ripening process and delays the harvest time. This aspect was seen in low berry °Brix and high TA. Vine size was highly positively correlated with cluster weight, while juice pH was highly negatively correlated with yield, Ts, and clusters per vine. Soil moisture, soluble solids and berries per cluster showed no relationship with any other variable.

DISCUSSION

1. Soil moisture

The dry side of the PRD treatment consistently had lower soil moisture values compared to the control. This might be because root density in the PRD treatment was higher at this particular depth (200 mm), causing higher water depletion compared to other treatments. Van Zyl (1988) indicated that root grapevine development is strongly related to moisture level in the soil profile. Roots grow in response to the available water supply and soil bulk density (Morlat and Jacquet, 1993).

Root growth pattern can be modified by timing and intensity of water stress. Root growth can decrease by severe soil water stress, although moderate stress can enhance it (Van Zyl, 1984). Root distribution is altered by the type of irrigation system used. Dry *et al.* (2000a) showed that the pattern of grape root distribution changed when PRD strategy is used. More roots were developed in deeper layers of soil and a larger root system was observed under this irrigation system. Soar and Loveys (2007) found a significant increase in total root mass under the drip line, particularly 25-50 cm below the surface. However, others showed that roots tend to proliferate in regions of high water availability in zones where water is unevenly distributed (Gallardo *et al.*, 1994). The hydraulic conductivity of grape roots also increased noticeably under a locally restricted water supply (Poni *et al.*, 1992).

Vines from PRD treatments compensate for restricted water on the dry side by an increase in root development in moist soil layers on the wet side, and in lower horizons on the dry side (Dry *et al.*, 2000c). Soil moisture measured by Profile Probe at any depth did not show high fluctuations over the season in the wet or dry zones of the PRD treatment. This might be explained by the fact that these vines had well-established root systems at the time the experiment was initiated, and consequently further root development did not occur that could demonstrate effects of these irrigation strategies. At the 30 cm depth, soil moisture was lower in the dry zone compared to other depths. Once again, one could speculate that the water depletion rate was higher due to higher root density at that depth for reasons already mentioned (Van Zyl, 1988).

There are contradictory theories in the literature about vine root development under PRD irrigation strategy. Soil water content of the wetted side of PRD plants was depleted more rapidly than the same side of control plants (Kang *et al.*, 2002), indicating the root system can partially compensate for the increasingly limited water availability of the dry side. Episodes of soil drying and re-watering can enhance the extension and initiation of secondary roots (Liang *et al.*, 1996). ABA accumulates in shoots and roots during stress (Milborrow and Robinson, 1973) and it is possible that ABA may be involved in controlling changes in plant growth, such as enhanced root to shoot ratios (Watts *et al.*, 1981) that occur in response to lack of water.

Soil moisture in non-irrigated and RDI treatments was consistently lower than the PRD and 100ET treatments. This indicates that the control and RDI treatment had almost the same effect on soil and vine water status. These data corroborate findings showing that vines are more responsive to volume of water applied through irrigation and less to the strategy used to deliver it (Gu *et al.*, 2004). However, soil moisture in the PRD treatment was lower than the 100ET treatment and higher than the non-irrigated and RDI vines. This can be explained more readily in the dry and hot 2007 season. ABA produced in drying roots has an impact on root growth (Dry *et al.*, 2000a,b). These authors indicated that vines subjected to PRD irrigation increased root development in deeper soil layers compared to a fully irrigated control. The physiological effects of ABA and cytokinins are generally antagonistic (Khan, 1975) and it is possible that ABA promotes lateral root formation by inhibiting the action of endogenous cytokinins. An important mechanism of plant response to PRD may be an increased ability to access soil resources (Kang *et al.*, 2002).

Soil water depletion patterns were similar and more stable in 2006 and 2007 than in 2008, when rainfall and cool temperatures during the growing season occurred. High amplitude in soil water depletion levels between treatments during dry and hot years is explained by oscillatory transpiration during the day (Rose and Rose, 1994) and high soil evaporation. This might be a consequence of low canopy development under low water status and less soil shading. In general, soil moisture can be a reasonable measure of plant stress. However, although determination of soil moisture is commonly performed and relatively easy to do, there are several drawbacks that limit its use in water management decisions in viticulture. First, the same level of plant water status can occur at very different soil water availabilities and second, there are always uncertainties where the actual zone of active water uptake is located (Davenport *et al.*, 2008). There is evidence that the type of irrigation applied affects the lateral spread of roots through the soil moisture pattern. In South Africa, drip irrigation reduced the lateral spread of root systems, and resulted in higher root densities within the drip zone compared to microsprinkler irrigation (Van Zyl, 1988).

2. Transpiration and leaf water potential

The same volume of water was applied in the PRD and 100ET treatments, but Ts values were close to the control in the PRD treatment. This reduction in Ts in the PRD treatment might have been due to higher ABA concentrations in the roots and leaves (Stoll *et al.*, 2000a,b). As expected, the Ts rate was lower in PRD than in the 100ET treatment. However, PRD closely followed the non-irrigated and RDI treatments in August. This was due to the fact that vine water status is not the only factor that controls stomatal opening. Other factors such as temperature, solar radiation and vapour pressure deficit affect stomatal opening and consequently Ts rate (Hetherington and Woodward, 2003). The results from this study are in agreement with others who showed that PRD treatments reduced Ts rate per unit of leaf area, relative to full irrigation (Dry and Loveys, 1999; Stoll *et al.*, 2000a,b).

Effects of PRD on both potted and field-grown grapevines include a reduction in stomatal conductance and Ts rate (Dry and Loveys, 1999; Dry *et al.*, 2000a,b). Chemical signals such as ABA produced in the dry roots reduce stomatal conductance and vegetative growth, while fully hydrated roots maintain favourable water status in the aerial parts of the plant (Dry and Loveys, 1999). However, most irrigation studies conducted on PRD calculated the amount of water needed in PRD treatments as a percentage of ET_c. The results from this work therefore cannot be compared with those found in most previous studies where PRD strategy was used, since in the present trials, full water replacement was applied. Moreover, these data showed that PRD treatment affected transpiration despite the fact that the region is cool and humid.

Irrigation treatment impacted leaf ψ, particularly in 2007. In some studies, leaf ψ in non-irrigated vines has been reported as high as -1.6 MPa in humid regions (Düring and Loveys, 1982). Leaf ψ values between -1.4 MPa in well-irrigated post-veraison treatments (3.5 mm daily) and -1.9 MPa in low irrigated treatments (1 mm daily) were reported for Sauvignon blanc in Israel (Naor *et al.*, 1993). Their values were much lower, even in the well-irrigated treatment, than those in this trial. Since their experiment was in a semi-arid region (Golan Heights), it is difficult to compare responses to treatments, even though they used the same cultivar. Moreover, they stated that the low leaf ψ was attributed to the relatively high vapour pressure deficit, wind speed and solar radiation. This indicates that variations in leaf ψ do not result from soil water availability changes but rather are a response to temporal variations in meteorological conditions (Naor *et al.*, 1993).

These data suggest that Sauvignon blanc is an anisohydric cultivar, showing high variation due to soil moisture content, especially in 2007. Generally, as a soil dries out a decrease in stomatal conductance is associated with a reduction in leaf ψ. Isohydric plants tend to maintain a more constant water status by controlling stomatal conductance from an interaction between hydraulic and chemical signals, whereas anisohydric species tend to have less rigid stomatal control, which allows a greater fluctuation in leaf ψ with decreasing soil ψ (Tardieu and Simonneau, 1998) or increasing evaporative demand (Soar *et al.*, 2006).

3. Shoot growth and vine size

Winter pruning weights provided an assessment of vine size. One noteworthy observation was that vine size was not correlated with shoot growth rate in some treatments. These results do not totally agree with studies in which reductions in shoot and fruit growth were found in vines under water stress (Bravdo *et al.*, 1985). The PRD treatment, which also received 100% ET_c, had lower vine size than the RDI treatment. This might be explained by the higher production of ABA in the PRD treatment, which affects the shoot growth rate (Stoll *et al.*, 2000b). Many studies have showed conflicting results in the PRD experiments, probably because many studies used a combination of PRD and deficit water strategy. Evaluation of PRD and RDI strategies on Sauvignon blanc in California found that Ts rate, pruning weights, number of lateral shoots and fruit TA were affected only by irrigation volume and not by method of irrigation used (Gu *et al.*, 2004). These data showed that both the method and the water regime can affect vine performance. However, the pattern is also affected by the climatic conditions from one particular year. Moderate water stress can reduce vegetative growth without affecting photosynthetic activity, which favours the partitioning of the carbohydrates (Carbonneau and Deloire, 2001). However, deficit irrigation treatments of 20 and 40% of ET_c led to no differences in vegetative growth (Centeno *et al.*, 2005). Findings from this study are similar to results from Sauvignon blanc trials in Marlborough, New Zealand that indicated that RDI decreases vine size (Greven *et al.*, 2005).

4. Yield components

In 2008, the PRD treatment had the lowest yield, mainly due to lowest clusters per vine. This might be explained by treatment differences in hormone levels such as gibberellic acid during cluster initiation in the previous sunny and dry 2007 season (Srinivasan and Mullins, 1981). In a study on water use by Sauvignon blanc vines in Marlborough, New Zealand, reducing water by 40% did not lead to differences in yield or berry composition (Greven *et al.*, 2005). In Marlborough, where irrigation is normally supplemental rather than essential, seasonal differences are likely to be greater than irrigation treatment differences (Greven *et al.*, 2005). Results from our study, as with Greven *et al.* (2005), did not fully clarify the beneficial effects of PRD vs. RDI, even if some variables were affected by them. This might be explained by climatic variation throughout the period studied. A study conducted on Thompson Seedless indicated that a 50% reduction in irrigation volume resulted in only a 26% yield loss while a 70% reduction resulted in only a 35% yield loss (Grimes and Williams, 1990). Lack of yield reductions in RDI treatments was explained by the fact that the vines did not reach the critical leaf area to fruit weight ratio (Gu *et al.*, 2004).

5. Berry, must, and wine composition

Soil moisture and leaf ψ were inversely correlated with wine ethanol in 2006, ethanol and berry °Brix in 2007, and berry pH in 2008, as well as directly correlated with TA in 2007 and 2008. This indicates that high water status negatively affects fruit composition, particularly if the other two climatic factors (temperature and solar radiation) are low throughout the season. However, there was no consistent pattern in berry, must, and wine composition among irrigation treatments from year to year, suggesting that other climatic factors might have affected composition. For example, PRD grapes had higher °Brix than 100ET in one of 3 years studied. °Brix values can be reduced either due to a dilution effect (Bravdo *et al.*, 1985) or competitive vegetative sinks (Bravdo and Hepner, 1987). Because of high climatic variation over the period of this trial, both explanations are plausible to justify the variation in °Brix. In Bordeaux, a TA of 7.5 g/L is considered optimum for the production of well-balanced white wines (Ribéreau-Gayon *et al.*, 1998). In this study, a TA of 7.5 g/L was only found in the 100ET treatment in 2007. However, berry TA values were highest in 2006 despite more rainfall, lower temperatures, and lower solar radiation in 2008. The results are partially in agreement with studies conducted in Israel, where moderate TA reductions were observed under water deficits (Bravdo *et al.*, 1985). In contrast, an Australian study reported no effect of water status on berry TA (McCarthy *et al.*, 2000). However, most have shown TA increases and °Brix decreases under excessive irrigation, resulting in delayed fruit maturation (Hepner *et al.*, 1985). An irrigation study on Tempranillo suggested that higher yields in irrigated vines did not have any adverse effects on must composition, because the synthesis and accumulation processes were able to offset dilution effects (Esteban *et al.*, 1999). Severe water deficits resulted in low berry °Brix, low TA and high pH, because of low malic acid concentration (Goodwin, 2002). Berry composition affected by deficient or excess water is normally not favourable for producing high-quality white wines (Peyrot des Gachons *et al.*, 2005). In general, the response of berry pH to soil moisture varies. Berry pH increased with irrigation for Carignane (Freeman and Kliewer, 1983), but not for Cabernet franc (Matthews and Anderson, 1988), or Cabernet Sauvignon (Bravdo *et al.*, 1985). In Shiraz, no response of berry pH to irrigation was reported (McCarthy *et al.*, 2000). However, a reduction in pH was noted in PRD-irrigated fruit compared to control vines due to reduced canopy density (Dry *et al.*, 2000c).

PRD has been associated with an improvement in berry composition due to increased control over vegetative growth, leading to increased light penetration into the fruiting zone (De Souza *et al.*, 2005). These authors found that PRD maintained yield, but berry composition was not improved compared to fully irrigated vines. In the present study, PRD did not show entirely consistent effects on yield components and berry composition. This might be explained by the climatic variation from year to year or the amount of water used. Since in most previous experiments, PRD treatments replaced just a fraction of ET_c, it is possible that the real effect of PRD was determined by water deficit and not by irrigation strategy (Gu *et al.*, 2004).

Musts and wines from PRD and RDI treatments had the same TA but different pH values in 2006. The pH was lower in the RDI musts. Since berry pH was not correlated with TA, the pH variation was likely due to treatment effect on K^+ uptake rather than acid metabolism (Boulton, 1980). The 2007 must and wine pH values were lower compared to 2006 but treatment differences were small. This suggests that malic acid metabolism and K^+ uptake in the berries were impacted in hot and dry years (Sipiora *et al.*, 2005). This is in agreement with Boulton (1980), who showed a strong relationship between K^+, acids and pH. In South Africa, a trial showed that the wine composition of Colombard was insensitive to irrigation (Van Zyl, 1984), while other irrigation studies on Chenin blanc and Sauvignon blanc (Myburgh, 2006) suggested that smaller berries as a result of reduced irrigation would not dramatically alter the composition of white wine.

6. Wine sensory analysis

Sensory attributes of Sauvignon blanc can vary considerably with climate and vintage. For instance, tropical fruit and boxwood (green) aroma were associated with cool-wet region style of Sauvignon blanc, while stone fruits and melon were associated with warm-dry climates (Myburgh, 2006; Peyrot des Gachons *et al.*, 2005). Unfortunately, having sensory data from just one season did not allow one to draw strong conclusions of a vintage effect on the wine sensory profile. Our data are nonetheless in agreement with Peyrot des Gachons *et al.* (2005), who found that in dry vintages, highest aroma potential was achieved in plots with the greatest water reserves, while in wet vintages, highest aroma potential was achieved in plots with lowest water reserves. Water deficits reduced berry size but there was no relationship between berry size and berry aroma precursor concentration and associated sensory attributes in Sauvignon blanc, which is consistent with our 2007 data.

The thiol 4-mercapto-4-methylpentan-2-one is responsible for the box tree and hay aromas in Sauvignon blanc wines (Darriet *et al.*, 1995), while 4-mercapto-4-methylpentan-2-ol smells of citrus zest, and 3-mercaptohexan-1-ol correspond to grapefruit and passion fruit flavour (Tominaga *et al.*, 1998). The concentration of volatile thiols responsible for most of the flavour and aroma in Sauvignon blanc wine is directly related to the concentration of their precursors, but only a small percentage of the precursors are effectively transformed into aroma during vinification (Peyrot des Gachons *et al.*, 2000). Thiols have a higher degree of correlation with Sauvignon blanc sensory attributes compared to methoxypyrazines (Lund *et al.*, 2009). The latter compounds are responsible for green-capsicum characteristics (Allen and Lacey, 1999). Our sensory data did not show an increase in intensity of any attribute related to fresh green vegetable characteristics, including wines from the 100ET treatments. This might be explained by the relatively high temperature and solar radiation during the 2007 growing season, which could have enhanced catabolism of methoxypyrazines in the berries (Marais, 1994). The typical "herbaceous-vegetative" Sauvignon blanc aroma profile is affected by origin/climate where the grapevines are grown, and decreases progressively as grape maturity increases (Allen and Lacey, 1999). Methoxypyrazines are also light sensitive and easily degradable to other components (Heymann *et al.*, 1986). According to previous findings, more vegetal character was expected in the 100ET treatment where the canopy size was larger and more cluster shade possibly occurred.

Overall, little research on the relationship among vine and soil water status, irrigation strategies and the sensory profile of Sauvignon blanc has been done. Dry (2004) reported that PRD has the potential to improve wine quality by increasing secondary metabolites such as phenolics and norisoprenoids that could also affect wine quality (colour, astringency, mouthfeel, aroma/flavour). These data also showed an increase in intensity of some of the aroma descriptors, which might be reasonably explained by changing the enzymatic activity under different water status level in the vine. The role of light in mechanisms of flavour biosynthesis appears to be of particular importance. Water status might have an indirect effect on flavour accumulation through its effect on the canopy size. Changes in flavour compounds as a result of leaf and cluster shading was more related to the effect of light rather than temperature (Morrison and Noble, 1990). Although the sensory data were not accompanied by chemical aroma and flavour compounds analysis, the Sauvignon blanc wine sensory profile had many of the distinctive characteristics for this cultivar, both fruity (citrus, tropical, gooseberry, passion fruit) and green (grassy, leafy, capsicum, asparagus) characteristics. However, their intensity seems to be affected by the different irrigation strategies used.

7. Overall effects of PRD

PRD irrigation strategies applied at deficit rates have generated a range of responses in vines. Some showed that vines are more affected by irrigation volume rather than method of application (Pudney and McCarthy, 2004). Others concluded that PRD applied at different levels of ET_c had no effect on physiology of peaches (Goldhammer *et al.*, 2002) or grapes (Gu *et al.*, 2004). The response of plants to PRD might be strongly influenced by environmental and management factors such as soil type, cultivar, vapour pressure deficit, irrigation frequency and level of deficit applied (De Souza *et al.*, 2003). In the present trials, the PRD effect might have been altered, especially in 2006 and 2008, by natural rainfall, and also by substantial horizontal movement of water through the soil profile due to the relatively high clay content. PRD irrigation strategy used in vineyards generates a unique physiological response distinct from conventional irrigation. By controlling water loss under high and low vapour pressure deficit, PRD improves water use efficiency (Collins *et al.*, 2008). Data from this study partially agrees with this finding.

CONCLUSION

This study is the first evaluation of PRD in a cool, humid climate of which we are aware. Using RDI or PRD in dry and warm years improved grape composition of Sauvignon blanc. Water status altered canopy characteristics, and affected vine physiology, but this was not necessarily translated every year into changes in grape composition. Irrigation therefore did not have consistent effects on yield components and berry composition. This lack of consistency might be because soil moisture was relatively high during two of three growing seasons, particularly when the irrigation treatments were initiated (around fruit set).

In very dry and hot seasons, like that of 2007, irrigation improved grape composition and wine aroma typicity. The balance between vegetative and fruity character of the Sauvignon blanc sensory profile was manipulated by soil moisture level. The RDI strategy was more consistent in its effects on growth and yield than PRD, 100ET, and non-irrigated treatments. RDI enhanced fruity aroma attributes, suggesting that this could be a viable strategy to improve grape and wine quality in cool areas. Whatever irrigation strategy might be used in industry or research, it is highly recommended that the irrigation systems be installed and used immediately after the vines are planted. As this trial indicated, use of irrigation in a mature vineyard with a well-established root system will make it more difficult to control water use efficiency, and the vines will take longer to respond at various deficit irrigation strategies in terms of yield and berry composition.

Despite improving the general vine physiology and fruit composition in dry years, more research should be conducted on PRD before strong recommendations can be made. One concern is that in humid climates, frequent rainfall might eliminate the effects of PRD. Moreover, in soils with high clay content, movement of water from irrigated zones by horizontal capillarity may reduce the localised effects of PRD. Nonetheless, it was noteworthy that “wet” and “dry” zones were apparent, even in seasons such as 2006 where rainfall was frequent. This study clearly showed that both ends of the plant water status spectrum (non-irrigated, 100ET) had a negative effect on vine performance, while moderate water stress, 25% ET_c in this case, had a positive effect on fruit composition. This contradicts a common belief among winemakers that irrigation always affects fruit and wine quality negatively. More work is also required to ascertain whether the quality improvement found in red grapes might also be achieved in white grapes in different seasons and different regions. PRD offers significant advantages over RDI in achieving these quality improvements. Certainly, the sensory profile for Sauvignon blanc could be manipulated through irrigation. More investigation is necessary into relationships of soil and vine water status and their effects on the chemical compounds responsible for the sensory profile of this cultivar.

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