EFFECT OF DIFFERENT IRRIGATION STRATEGIES ON VINE PHYSIOLOGY, YIELD, GRAPE COMPOSITION AND SENSORY PROFILES OF *VITIS VINIFERA* L. CABERNET-SAUVIGNON IN A COOL CLIMATE AREA

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Abstract

Aim: The efficacy of partial root zone drying (PRD) and regulated deficit irrigation (RDI) on vine physiology, yield components, fruit composition and wine sensory profiles of 'Cabernet-Sauvignon' was investigated in a cool climate region in Ontario, Canada.

Methods and results: Field experiments were conducted in a Cabernet-Sauvignon block in Niagara-on-the-Lake, ON Canada between 2006 and 2008. There were five treatments : non-irrigated control, PRD, full irrigation [100 % of crop evapotranspiration (ET_c)] and two levels of RDI (50 and 25 % ET_c). Treatments started immediately after fruit set and continued until post-veraison. Soil and vine water status were apparently controlled not only by the amount of water but also by the irrigation strategy used. In the PRD treatments, soil moisture, leaf water potential, and transpiration rate were generally lower than in 100 % ET_c but higher than non-irrigated and RDI treatments. Almost all treatments were different than in non-irrigated vines in fruit composition and wine sensory attributes. Wine sensory attributes differed considerably due to the amount of irrigation water applied in 2007. RDI strategies were more consistent than the PRD treatments in their effect on vine water status, grape composition and wine sensory profiles. Inconsistent patterns across seasons for some variables indicated that besides soil and vine water status, there were other factors that impacted vine physiology, yield components and berry composition.

Conclusions: RDI treatments improved wine quality when compared with full or either non-irrigated treatments. Overall, use of RDI irrigation or PRD during dry and warm years can improve grape composition in cool climates.

Significance and impact of the study: To the best of our knowledge, this is the first evaluation of PRD and RDI on Cabernet-Sauvignon in a cool humid climate. It suggests that although RDI strategies are more effective, PRD also has value, particularly in dry seasons.

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

Résumé

Objectif: L'efficacité du dessèchement partiel de la zone racinaire (PRD) et de l'irrigation déficitaire régulée (RDI) sur la performance de la vigne, la qualité des fruits et des vins de Cabernet-Sauvignon a été analysée dans une région au climat tempéré - (frais) en Ontario, au Canada.

Méthodes et résultats: Les expérimentations au champ ont été menées dans un vignoble planté avec du Cabernet-Sauvignon à Niagara-on-the-Lake, Ontario, Canada entre 2006 et 2008. L'essai comprenait cinq traitements : un contrôle non-irrigué, le PRD, la pleine irrigation [100 % de l'évapotranspiration des cultures (ETc)] et deux niveaux de RDI (50 et 25 % ETc). L'humidité du sol et l'état hydrique de la vigne ont apparemment été contrôlé non seulement par la quantité d'eau, mais aussi par la stratégie d'irrigation utilisée. Les vignes non irriguées ont montré des différences concernant la composition des raisins et les caractéristiques sensorielles des vins en comparaison des autres traitements. Les stratégies de RDI ont montré des effets plus uniformes que les traitements PRD quant à l'état hydrique de la vigne, la qualité des fruits et des vins. Des tendances contradictoires ont été observées selon les millésimes pour certaines variables indiquées, à côté de celles du sol et de l'état hydrique de la vigne, suggérant que d'autres facteurs ont influé sur la physiologie de la vigne, les composantes du rendement et la composition des baies.

Conclusions: Les traitements RDI ont amélioré la qualité du vin par rapport aux traitements de pleine irrigation ou du contrôle non irrigué. Dans l'ensemble, l'utilisation de l'irrigation RDI ou PRD pendant les années sèches et chaudes peut améliorer la composition des raisins dans les zones tempérées.

Importance de l'étude: A notre connaissance, il s'agit de la première évaluation des stratégies PRD et RDI sur Cabernet-Sauvignon dans un climat tempéré -frais et humide. Les résultats suggèrent que la stratégie RDI est la plus efficace, et dans une moindre mesure celle du PRD, lors d'un millésime chaud et sec.

Mots clés : Humidité du sol, potentiel hydrique foliaire, irrigation déficitaire régulée, dessèchement partiel de la zone racinaire, profils sensoriels des vins.

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INTRODUCTION

Irrigated vineyards are located mostly in "The New World", in areas where there is low rainfall during the growing season, and moisture in the soil profile is insufficient for healthy vine growth (McCarthy *et al.,* 2002). Despite using irrigation, "The New World" consistently produces very high quality wine, which would not be possible under natural conditions. Drought is not normally an issue in north-eastern North America. However, in the last decade, frequency of water shortages during active vegetative growth has increased. Exposure of vines to some degree of water stress during vegetative growth has been reported in cool wine regions (Van Leeuwen and Seguin, 2006; Zsófi *et al.*, 2009). In winegrape production, both drought and excess water should be avoided due to their negative effect on wine quality (Van Leeuwen and Seguin, 2006).

Vitis vinifera L. is considered a species adapted to drought stress. However, when water deficit is combined with other climatic factors such as high light intensity, temperature and vapour pressure deficit, it could become a major constraint for leaf photosynthesis (Flexas *et al.*, 1998). Water stress can determine changes in leaf physiology, including a reduction in stomatal conductance, photosynthesis and transpiration (Matthews and Andersonn, 1989). Grapevine vegetative growth is the first process affected by water restriction. Water deficits reduce shoot growth, yield, fruit size, and as a consequence, physiological changes, fruit composition and wine sensory attributes are likewise altered (Roby and Matthews, 2004). Studies in California revealed that different levels of water deficits generated significant differences in appearance, flavour, taste, and aroma among Cabernet-Sauvignon wines (Chapman *et al.*, 2004). Water restriction could favour polymerization of tannins, and subsequently decrease astringency and bitter flavours related to tannin monomers (Ojeda *et al.*, 2002).

Drought stress could be an issue in the vineyard that leads to economic losses if it is extended to a prolonged period of time. Severe water stress applied to container-grown Cabernet Franc vines decreased yield by 94 % due to reducing number of berries per cluster and berry weight (Hardie and Considine, 1976). Matthews and Anderson (1989) found yield reductions in Cabernet-Sauvignon under water deficits, and suggested that the large differences in yield occurred due to alterations in berry growth pattern. However, yield reductions resulting from prolonged water deficits depended on the stage of berry development when drought occurred (Hardie and Considine, 1976). For red winegrapes, some degree of water deficit during the growing season is beneficial for quality (Williams and Matthews, 1990). However, there are contradictory studies suggesting that fruit composition and wine quality of Cabernet-Sauvignon could be more related to variations in yield (Keller and Hrazdina, 1998), and this response could depend on how and when the yield variation is established (Chapman *et al.*, 2004). In general, irrigation can lead to increases in vine size and yield (Bartolomé, 1993). In berries, sugar concentration was affected by irrigation, which in some cases it increased (Bartolomé, 1993), or was reduced (Williams and Matthews, 1990). Irrigation could indirectly affect berry composition due to higher photosynthesis rates or higher stomatal conductance (Escalona *et al.,* 1999). Cabernet-Sauvignon is third in importance behind Cabernet Franc and Merlot in terms of red wine grape production in Ontario, with a yield of 3527 tonnes in 2007 (http://www.grapegrowersofontario.com). Although Niagara lies on the 43rd parallel and shares the same latitude with Bordeaux (France), there is still debate concerning the potential for consistent wine quality of Cabernet-Sauvignon, mostly due to high variation of weather from vintage to vintage. In Ontario, the wine industry could improve water use efficiency, and keep consistency in wine quality through application of deficit irrigation strategies. If it is managed properly, deficit irrigation could have a minimal impact on carbon assimilation compared to full irrigation (De Souza *et al.*, 2003). The irrigation strategy known as regulated deficit irrigation (RDI) has been proven to be a viable practice in the vineyard for controlling excess vigour, reducing pest and disease pressure, and improving wine quality (McCarthy *et al.*, 2002).

Partial root zone drying (PRD) is another irrigation strategy successfully used in some wine regions, and involves application of a reduced amount of irrigation to alternate sides of the vine root system (Dry and Loveys, 1998; Dry *et al.*, 2000 a, b). PRD strategy was developed based on observations that abscisic acid (ABA) originated in the drying roots reduces stomatal conductance, photosynthesis, and vegetative growth, and could ultimately trigger the final steps in the ripening process (Loveys, 1984). ABA regulates the biosynthesis of the primary and secondary metabolites during the grape berry ripening (Davies *et al.,* 1997). Increases in ABA levels during the berry maturation have been correlated with increases in soluble solids and anthocyanins (Palejwala *et al.*, 1985). Despite these effects, some have reported no differences between PRD and RDI in terms of grapevine performance (Gu *et al.*, 2004; Pudney and McCarthy, 2004).

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Most of the studies related to the effect of water stress and irrigation strategies on fruit composition and wine quality have been conducted in areas located in hot and dry regions. However, just few studies focused on the effect of water deficit on grape cultivars grown in cool climates. Therefore, there is a need for a better understanding of how irrigation affects the grape quality in a cool area. The objective of this research was to study the effect of different levels of water status on vine physiology, yield components, grape composition, and the wine sensory profile of Cabernet-Sauvignon, resulting from various RDI and PRD irrigation strategies in a cool area.

MATERIALS AND METHODS

1. Site description and experimental design

The trials were carried out in a commercial vineyard (Lambert Vineyards Ltd.) in the Niagara Peninsula of Ontario (43°13' N, 79°08' W, elevation 98 m), Canada, from 2006 to 2008. The experiment was set up in one Cabernet-Sauvignon block, grafted to SO4 (*V. berlandieri x V. riparia*) 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 fertilization with 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 [Ontario Ministry of Agriculture, Food & Rural Affairs (OMAFRA), 2007].

Soil type was Chinguacousy clay loam (gleyed brunisolic gray brown luvisol) with imperfect drainage (7 to 9 L/h). The wilting point of the Ap horizon (0 to 27 cm) was 13.3 % moisture, and the field capacity was 27.3 % moisture by volume. Bulk density varied between 1.25 g cm^{-3} in horizon A and 1.69 g cm^{-3} in horizon C (Kingston and Presant, 1989). The whole block had a subsurface drainage system, with tiles placed at a 60 cm depth in the middle of every row. Soil management consisted of mowed sod row middles with ≈ 1.0 m herbicided strips under the vines.

The experimental design was a randomized complete block arrangement, with five irrigation treatments and four replicates, with two rows on each side as a buffer. Irrigation was initiated at fruit set and continued four to five weeks post-veraison depending on the weather conditions. The treatments were: control (non-irrigated), PRD (100 % ET_c), full irrigation (100 % ET_c; hereafter referred to as 100ET) and two RDI (50 and 25 % ET_c; hereafter referred to as 50ET and 25ET, respectively). Each row was a treatment replicate, with 10 equally-spaced vines 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. 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 75 cm apart in the same row, each of which had its own valve at the end of the row. Drippers (1.5 L/h) were installed alternately to each other in each irrigation line 1.2 m apart in 2006. The volume of water used was calculated based on the reference evapotranspiration (ET_o), using the Penman-Monteith equation (Allen *et al.,* 1998), and adjusted to ET_c using a crop coefficient (K_c). 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). The drip line valves of the PRD treatments were each opened biweekly to irrigate half of the root system each time.

2. Soil water status

Soil moisture was assessed over a period of 3 years between 2006 and 2008. Data was collected from 10 vines per each treatment replicate starting one week before first irrigation treatment was imposed, and biweekly thereafter. 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. Data collection protocol and the equipment used were described in detail in Balint and Reynolds (2010). Measurements were taken in the row at 25 cm from the base of each trunk (10 cm from the dripper) and at 20 cm depth. In the PRD treatments, measurements were taken in the row on both sides of the vines.

3. Vine water status

Biweekly observations were recorded over the growing season to monitor vine water status. Data were collected 1-2 days before the irrigation treatments were applied. Midday leaf water potential (ψ) data was collected from mature leaves fully exposed to the sun between 1100h and 1400h using a Scholander-type pressure chamber (Soil Moisture Corp., Santa Barbara, CA). Measurements were

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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. An LI-1600 steady-state porometer (LICOR, Lincoln, NE) was used each season to measure leaf transpiration rate (Ts; μg H_2O cm^{-2}/s^{-1}) and leaf temperature. Transpiration was measured at saturating light only on clear days (no clouds), on leaves with approximately the same orientation to the solar radiation incidence.

Photosynthetic photon flux density (PPFD) readings were also collected by a LI-190S-1 quantum sensor installed on the porometer. Data was recorded on three exposed leaves from the same vines used to measure ψ. The sampling and collecting data protocols were described in detail in Balint and Reynolds (2010).

4. Yield and vigour components

The experimental vines were harvested 1 to 2 days before the commercial harvest date (third or fourth week of October) 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, titratable acidity (TA), colour intensity, hue, total anthocyanins, and total phenols. Number of berries per cluster was calculated from cluster weight and berry weight data.

During the 2006 and 2007 seasons, shoot growth rate was recorded using three readings collected when shoot growth rate was most active (June-July). One day before the irrigation treatments were initiated, three shoots of approximately the same length from three recorded vines were flagged. Shoots were randomly selected to avoid any 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 recorded vine was pruned to 40 nodes per vine during the dormant season (December to February).Vine size (pruning weights) was assessed by weighing the annual wood for each experimental vine after pruning using an electronic fish scale (Rapala, China).

5. Winemaking

In 2006, due to accidental harvesting of the experimental block by the grower, no grapes were available to process into wine. In 2008 (a wet and cool year), due to high vegetal character in the grapes from all treatments, no experimental wines were made. Grapes were processed into the wines only in the warm 2007 vintage. At harvest, 30 kg of grapes from each treatment replicate were processed into wine following the winemaking protocol described elsewhere (Reynolds *et al.*, 2007). Grapes from each treatment replicate were de-stemmed, crushed and treated with SO_2 solution at 20 mg/L. Each treatment replicate was fermented in duplicate in food grade 20-L plastic pails. They were inoculated with Lalvin Selection ICV 254 (*Saccharomyces cerevisiae*) yeast (Lallemand Inc., Montreal, QB). During the fermentation, all pails were kept in a controlled temperature room where temperature was set up to 24 °C. Fermentation lasted between 4 to 7 days. The caps were punched down manually three times daily (morning, noon and evening). After the caps fell, each fermentation treatment replicate was pressed off individually in a basket bladder press (Enoagricola Rossi s.r.l., Calzolaro, PG, Italy) at a maximum of 2 bars pressure, and then transferred to a 20-L carboy. After 10 days, when fermentation was completed, the wines were racked and inoculated immediately with malolactic bacteria *Oenococcus oeni* (Lalvin VP41, St. Simon, France). The wines underwent malolactic fermentation at 23 °C under a carbon dioxide atmosphere, and completion was confirmed by paper chromatography. Replicate 250-mL wine samples were taken for wine composition analyses (ethanol, TA, pH, colour, anthocyanins, and total phenols). Upon completion of malolactic fermentation, all wines were racked a second time, and kept for 10 days at -2 °C for cold stabilization. At bottling, the wines were sulphited at 30 mg/L and filtered using 0.45-μm pad and 0.2-μm cartridge filters. In January, wines were bottled under cork, and then stored at 12 °C in the wine cellar until sensory analysis.

6. Berry, must, and wine composition

Berry, must and wine samples were analyzed using similar protocols as those described in Balint and Reynolds (2010). 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) to remove any debris. The clear juice was used for soluble solids (°Brix) measurement

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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). A portion of the clear juice was also used for determination of A_{420}, A_{520}, total anthocyanins, and total phenols. Colour analyses were conducted according to a modified method provided by Mazza *et al.* (1999). Intensity and hue were calculated from absorbance values measured at 420 nm and 520 nm on an Ultrospec 2100 pro UV/VIS spectrophotometer (Biochrom Ltd., Cambridge, UK). Undiluted berry samples were analyzed through a 1-mm quartz cuvette, and the data were then multiplied by 10 to give 10-mm equivalents. The zero absorbance reference for berries consisted of 120 g/L glucose, 120 g/L fructose and 10 g/L tartaric acid in distilled water. Colour intensity was calculated as $A_{520} + A_{420}$; hue was calculated as A_{420}/A_{520}. Anthocyanins were measured using the pH shift method (Fuleki and Francis 1968), and total phenols were measured using the Singleton and Rossi method (1965), both on an Ultrospec 2100 pro UV/VIS spectrophotometer.

Musts were analyzed for °Brix, TA, and pH, and wine samples were analyzed for TA, pH, total anthocyanins, and total phenols as described above. Ethanol concentration was measured by gas chromatography (GC). The wine samples were filtered through 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 %; and 1.5 %) were combined with 10 mL of 100 % 1-butanol in 5-mL volumetric flasks, as an internal standard. 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 (He) was passed through an in-line Chromospec 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.

7. Sensory analysis

Wines from 2007 vintage were subjected to sensory analysis. A total of 10 judges with ages ranging from 23 to 58 were involved in the sensory work over a 3-month period. The group was composed of volunteer Brock University faculty, staff, and students from the viticulture and oenology program. They were selected based on their availability and motivation. All volunteers underwent prior sensory training.

Discrimination test. A modified alternative forced choice test 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 existed between treatments, what the basis for those differences might be, and whether the panellists were reliable. The test ran over a 2-week period, with two sessions per day and 2 days per week. Data were thereafter digitized and subjected to analysis of variance.

Descriptive analysis. In each session, panellists tasted five wine samples (non-irrigated, PRD (100 % ET_c), Full (100ET) and two RDI (50ET and 25ET)). Six training sessions were run over a period of 3 weeks. For sensory training, the panellists tasted wines from all irrigation treatments. Samples used for training purpose came only from two field replicates. The list with the descriptors was adjusted until all panellists agreed with definitions (Table 1). Following discussions with the panellists on the scale that should be used for data collection, along with technical advice from Compusense Inc. (Guelph, ON; the software provider for the sensory laboratory), it was decided that a two-way unstructured scale with verbal descriptions at the end points would be most appropriate (Ledahudec and Pokorny, 1994).

8. Data analysis

Field (ψ, Ts, soil moisture), fruit and wine chemical data were analyzed using SAS statistical package (SAS Institute; Cary, NC). Using generalized linear model, analysis of variance was performed on physiological and chemical data. Duncan's multiple range test was used for means separation for all data sets (field, chemical and sensory). Dunnett's *t*-test was used to determine 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). A three-way analysis of variance (irrigation treatment, judge, replicate) was also performed on sensory attributes to determine main effects and interactions. Principal components analysis (PCA) was performed each season on the means of field data, yield components, chemical data, and sensory scores of aroma and flavour descriptors.

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Table 1. Attributes and their standard references used for sensory evaluation of Cabernet Sauvignon wines.

Sensory attribute	Reference standard (prepared in 100 mL base red wine Kressmann -France)
Dark fruit	10 mL black currant concentrate (Ribena), 20 g of ED Smith wild fruit jam -blueberry and blackberry)
Red fruit	20 g mixture of fresh strawberry and raspberry (California)
Sour cherry	10 g of pulp sour cherries (canned)
Prune	20 g of fresh prune puree (Mexico)
Chocolate	No name (No Frills) – 5 g of cooking chocolate
Cooked vegetable	Mixture of fresh green pepper (4 g) and asparagus (5 g) Del Monte- cooked for 30 s in microwave and left 24 h in 100 mL of base wine
Tobacco	1 g of processed tobacco leaves (24 h maceration in 100 mL base wine)
Acidity	1.5g tartaric acid /L water
Astringency	0.3 g aluminum sulfate (Sigma) /L water

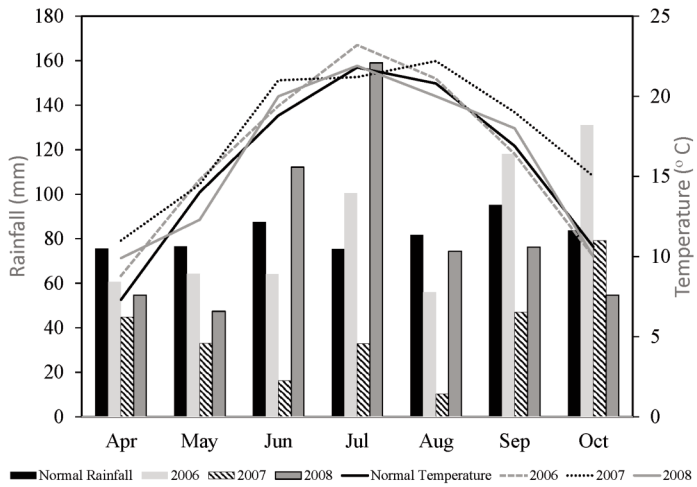


Figure 1. Monthly rainfall (mm) and mean temperatures (°C) April - October, 2006-2008 at Virgil Station, Niagara-on-the-Lake, ON, Canada. Normal rainfall and temperature values represent 30-year means (www.weatherinnovations.com).

Partial least squares regression (PLS) was performed on the field, chemical and sensory data to determine further relationships among these data.

RESULTS AND DISCUSSION

1. General meteorology and phenology

The 2006 and 2008 years had wet growing seasons with a total rainfall of 575 and 542 mm, respectively, from April 1st to October 31st (Figure 1). Compared to the other years of the experimental period, 2007 was the driest one with a total rainfall of 279 mm during the growing season, which was approximately two fold less than the same period in 2006 and 2008. In 2007, particularly May to July, temperatures were also considerably higher than average. Analysing rainfall data for the 3-year period (2006 and 2008) helped for a better understanding of the necessity of this project (Figure 1). In the Niagara Region for the last decade, at least 6 years were under water shortages during the growing season (Reynolds, 2008). This temporal variability of temperature and precipitation had a great impact on the cultivar's phenology. Veraison occurred in 2007 in the first week of August (±4 days depending on the irrigation treatment), while in the relative cool and wet years of the experiment (2006 and 2008) veraison occurred in the last week of August. Also, the weather conditions during growing season shifted the harvest dates (October 24th in 2006, October 17th in 2007 and October 30th in 2008).

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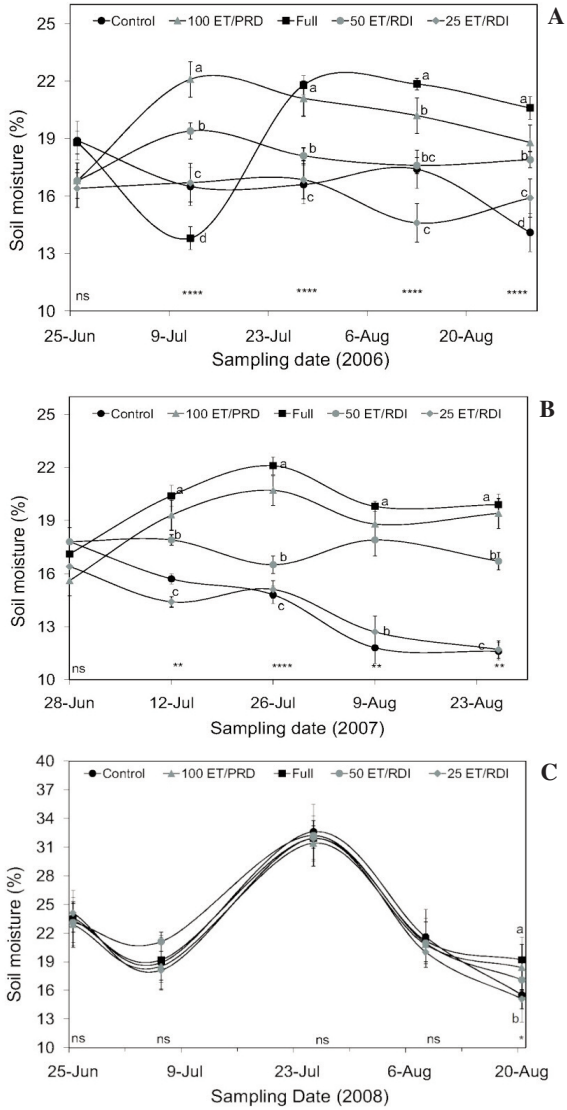


Figure 2. Impact of irrigation treatments on soil moisture (%) of Cabernet-Sauvignon grapevines, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006 (A), 2007 (B) and 2008 (C).

Control (non-irrigated); PRD - partial root zone drying (100 % ETc); Full - conventional drip irrigation (100 % ETc); RDI - regulated deficit irrigation (25 and 50 % ETc); 25, 50, 100 % are the percentages of water replaced in the soil. *, **, ****, ns: Significant at $p < 0.05$, 0.01, 0.0001, or not significant, respectively. Letters represent means separated at $p < 0.05$, Duncan's multiple range test.

2. Soil moisture

Soil moisture followed different trends in each year for the period studied. In 2006, although rainfall was close to that of a normal year, a distinct separation was observed among the irrigation treatments. The PRD and 100ET treatments had higher soil moisture compared to the control throughout the season, except for inexplicably very low values in the 100ET treatment, on 12 July (Figure 2A). However, soil moisture was lower in the PRD than the 100ET treatment at the last two sampling dates. Overall, the PRD treatment was very close to the 100ET treatment. In the 50ET RDI treatment, soil moisture was higher than both control and 25ET RDI, only at two sampling dates. The 25ET RDI treatment closely followed the same trend as the control. Soil moisture did not drop below wilting point at any sampling date. The lowest value (13.6 %) was found in the control on the last sampling date, and the highest in the PRD treatment (22.3 %) on the second sampling date.

In 2007, there was a better separation between treatments. PRD and 100ET treatments followed the same trend, higher than control and RDI treatments throughout the season (Figure 2B). The control and 25ET RDI were close to wilting point most of the growing season. They had a downward trend throughout the season, reaching a minimum on the last sampling date (12.2 %). The 50ET RDI treatment had almost no fluctuation, and its soil moisture was around 18 % throughout the season. Although 2007 was a hot and dry year, soil moisture in the PRD and 100ET treatments had a steady trend, which indicated that the theoretical calculation for water needs was accurate, and the water applied weekly through irrigation was almost all lost through transpiration and evaporation. The soil moisture in the 25ET RDI indicated that the amount of water supplied was not enough to keep consistent high moisture in the soil. Since the water demand was much higher at the end of the season because of both the ripening process and high vapour pressure deficit, 25ET RDI had almost no effect on soil moisture (Figure 2B).

In 2008, differences between treatments occurred on the last sampling date because irrigation treatments were not applied until veraison due to sufficient soil water reserves prior to that point (Figure 2C). Soil moisture followed the same trend as in a related Sauvignon blanc trial (Balint and Reynolds, 2013), with a minimum in the first week of July and at the end of August (Figure 2C). However, during most of the 2008 season, soil moisture was close to field capacity (27.3 % soil moisture, 33 KPa; Kingston and Presant, 1989), and did not drop below wilting point at any sampling date. In 2008, soil moisture followed the rainfall distribution with little variation among treatments. It was expected much more differences among the treatments even in such a wet year. However, it was possible that more variation in soil moisture to occur at higher depths due to previous irrigation history. It was assumed that the

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irrigation treatments made a difference on root system development in the previous seasons. Therefore, it was expected the soil moisture to be depleted at different rates because of the effect of soil moisture on the root distribution and density from the previous year. However, none of the expectations on soil moisture trend was observed in 2008. Perhaps, an obvious effect of the irrigation treatments might be seen in a long time trial. Also, consistent moisture on the whole soil profile in all treatments accompanied with low Ts rate did not have a distinct effect on the canopy development, and as a consequence no effect on water moisture depletion rate between treatments was observed in 2008.

Veihmeyer and Hendrickson (1950) stated that it is more important to know the occurrence or absence of periods with dry soil during the growing season when the soil moisture data is interpreted rather than the tabulation of the amount of water applied. Since irrigation was applied and the measurements were taken biweekly, the daily water depletion rate could not be assessed. Also, information about how long the vines were under water stress was not available, especially in RDI treatments, during one-week periods. Another interesting observation was that in PRD treatment soil moisture was slightly lower than in the 100ET treatment in 2006 and 2007, although in both treatments water was applied at 100 % ET_c replacement. This could be explained by the fact that the vines compensate for the loss of available water on the drying side by a relative increase in root development in moist soil layers, not only in the wet side but also in the deeper part of the drying side (Dry *et al.,* 2000 b). Pellegrino *et al.* (2005) stated that indicators of vine water status based on soil water measurements (soil water potential or soil water content) are not only time consuming but also they have questionable value in those vineyards with considerable spatial variation in depth and lateral spread of roots. This was not the case in our experiment since the irrigation treatments affected the soil water status in all years studied except 2008, the wettest year of the experimental period. However, the best discrimination between our treatments was observed in very dry and hot seasons.

Soar and Loveys (2007) showed that conversion of one vineyard from sprinkler to drip irrigation resulted in an increase in total root mass (volume) under the drip line, particularly at 25-50 cm below the surface. They also indicated that root distribution (according to root diameter class) was not only influenced by soil texture but also by irrigation history. The largest increase in root-length density under drip irrigation occurred for roots with diameter between 1 and 4 mm. Grapevines under sprinklers, and later converted to drip irrigation, had larger root systems compared to the vines maintained under sprinklers. They concluded that vines established under sprinkler irrigation and then converted to drip coped better with drought due to these additional roots. Although root distribution or density was not measured in our study, Soar and Loveys' findings support the soil moisture data, especially from the PRD treatment, which did not differ from the classic 100ET treatment.

3. Transpiration

In 2006, Ts was highest in full irrigated and PRD treatments (Figure 3A). This pattern was consistent throughout the season. Ts rates reached a maximum in the first week of August, with a peak of 13.6 µg $H_2O/cm^{-2}/s$ found in the 100ET treatment. The pattern showed a decreasing trend until the end of August for all treatments. In 2007, all the treatments followed the same trend, with the lowest Ts occurring in the control and the 25ET (Figure 3B). Since little rain occurred, data showed little variation in this trend at sampling dates during the growing season. In 2008, Ts showed the same trend as soil moisture (Figure 3C). The minimum Ts value was recorded at the end of August. Even with so much moisture in the soil, Ts was lower in 2008 than in 2006 in all treatments, possibly due to low temperature and solar radiation (data not shown). Our Ts values were similar to those of Reynolds *et al.* (2005, 2007), who found high Ts variation among several irrigated treatments in the same area. These authors found that Ts responded differently not only to the irrigation strategy but also to the cultivar used. Ts varied between 0.73 and 5.07 µg H_2O cm^{-2}/s^{-1} in Niagara grapevines (Reynolds *et al.,* 2005) and reached a maximum (around 13 µg H_2O cm^{-2}/s^{-1}) in fully irrigated Chardonnay vines (Reynolds *et al.,* 2007). However, in one experiment conducted in California, testing the effect of PRD and RDI treatments on Sauvignon blanc grapevines, Ts ranged from 3 to 25 µg H_2O cm^{-2}/s^{-1} (Gu *et al.* 2004).

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, and thus, improving water use efficiency (Dry *et al.,* 2000 a). Although in 2006 and 2007 vines from PRD treatment had lower Ts rates than those from the 100ET treatment, the treatments were different on just a few sampling dates. This might be explained by differences in the ABA concentration of xylem sap due to a hormonal dilution effect or inhibition of

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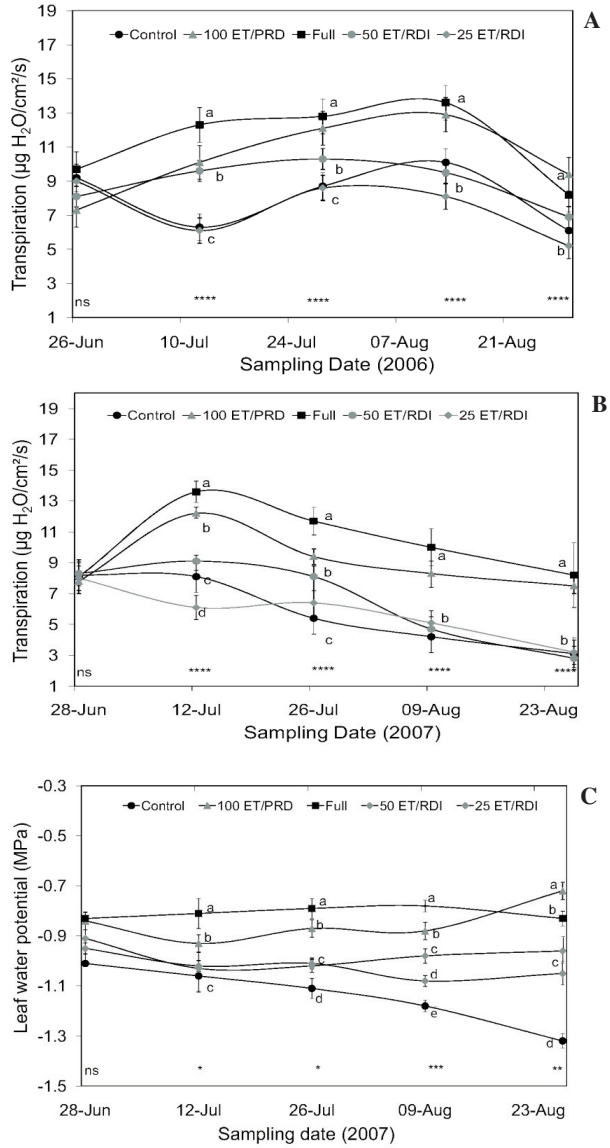


Figure 3. Impact of irrigation treatments on transpiration rate of Cabernet-Sauvignon grapevines, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006 (A), 2007 (B) and 2008 (C).

Control (non-irrigated); PRD - partial root zone drying (100 % ETc); Full - conventional drip irrigation (100 % ETc); RDI - regulated deficit irrigation (25 and 50 % ETc); 25, 50, 100 % are the percentages of water replaced in the soil. *, ****, ns: Significant at $p < 0.05$, 0.0001, or not significant, respectively. Letters represent means separated at $p < 0.05$, Duncan's multiple range test.

its biosynthesis. In these circumstances, PRD could have been interrupted by natural rainfall and any substantial horizontal movement of water through the soil profile due to the relatively high clay content. Consequently, RDI treatments generally produced a higher magnitude of response in terms of vine water status.

Drip irrigation and PRD particularly, applied at deficit rates, have generated various responses in vines from different experiments. Pudney and McCarthy (2004) showed that vines were more affected by irrigation volume rather than the method of application. Other studies concluded that PRD applied at different water levels had no effect on physiology and vine growth (Gu *et al.,* 2004). These apparent contradictions could be related to differences in the intensity of the chemical signalling under PRD irrigation. This seems to be dictated by the type of soil, the prevalent rainfall and evaporative demand in the region, as well as the frequency of switching irrigation from one side of the root zone to the other (Dry *et al.,* 2001) which could support the data variability.

The role of ABA in regulating stomatal aperture and consequently water loss has been studied widely in grapevines, both in pot and field experiments (Loveys, 1984; Stoll *et al.,* 2000). Environmental factors such as sunlight, along with leaf water status and xylem signals (e.g., cytokinins, ABA) act directly or indirectly on stomatal aperture, and thus, a particular stomatal aperture results from a combination of these factors (Webb and Hetherington, 1997). In general, maximum transpiration rate could be achieved at 20-35 °C and is restricted by temperatures < 5 °C or > 45 °C. The effects of temperature on stomatal behaviour are closely related not only to metabolism, enzymatic activity and hormones but also to external plant factors such as air vapour pressure (Jarvis, 1976). Part of the transpiration results might be explained by this complex interaction, especially in 2007 and 2008.

4. Leaf water potential

Leaf ψ followed a different trend in each year of the period studied. In 2006, the control decreased from -1.0 to -1.2 MPa through the season, while the irrigated treatments fluctuated between -0.8 and -1.0 MPa, with the highest leaf ψ in the 100ET and PRD treatments (Figure 4A). In 2007, the control decreased from -0.9 to -1.3 MPa throughout the season, with the lowest value reached at the end of August (Figure 4B). The RDI treatments were lower than the PRD and 100ET treatments, and higher than control. Except the control, all other treatments showed a steady trend throughout the season but different than each other (Figure 4B). This could indicate that the vine hydraulic conductivity responds not only to vapour pressure deficit (data not shown) but also to the soil water status. In 2008, the 100ET and PRD treatments were > -1.0 MPa, with little

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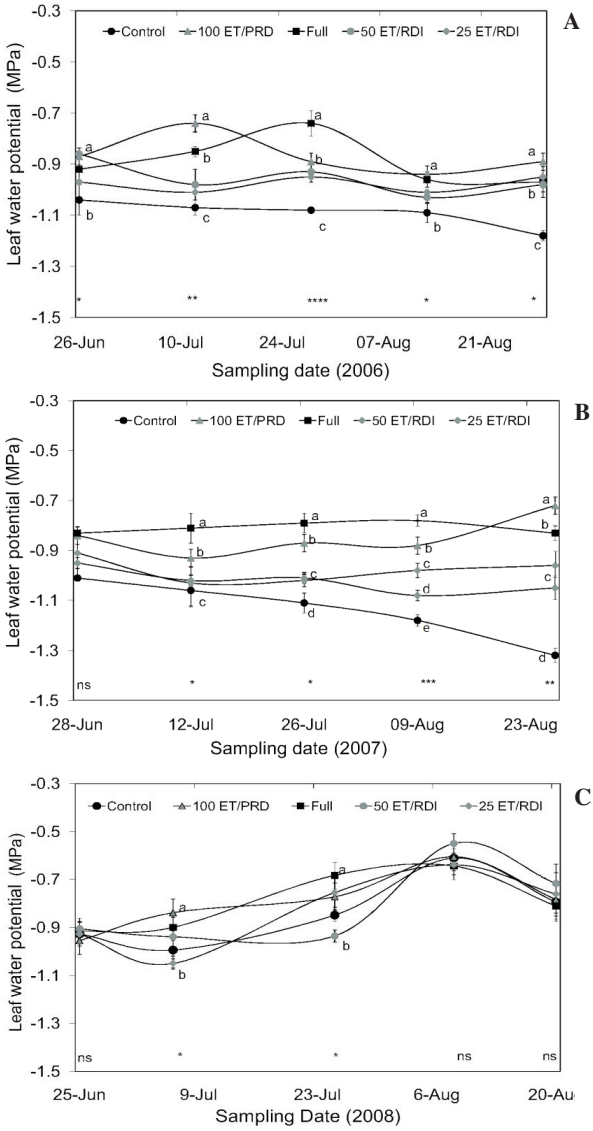


Figure 4. Impact of irrigation treatments on leaf water potential of Cabernet-Sauvignon grapevines, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006 (A), 2007 (B) and 2008 (C).

Control (non-irrigated); PRD - partial root zone drying (100 % ETc); Full - conventional drip irrigation (100 % ETc); RDI - regulated deficit irrigation (25 and 50 % ETc); 25, 50, 100 % are the percentages of water replaced in the soil. *, **, ***, ****, 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.

fluctuation during the season (Figure 4C). All treatments had an upward trend throughout the season, except for the last sampling date when leaf ψ decreased in all of them. However, all treatments were > -0.8 MPa on the last sampling date. The highest value was observed at pre-veraison in 50 % RDI (-0.5 MPa) while the lowest leaf ψ was found in 25 % RDI on the second sampling date. Surprisingly, in 2008, although only three irrigation treatments post-veraison were applied, there were differences among treatments for leaf ψ that could indicate some carryover effect from the previous season.

Williams and Matthews (1990) found that leaf ψ decreased throughout the season even for vines that were well watered, which supports the present results (Figures 4A to C). Leaf ψ of well-watered grapevines is a linear function of both ambient temperature and vapour pressure deficit, which means that leaf ψ decreases as both environmental variables increase (Williams and Baeza, 2007). Williams and Araujo (2002) reported that all methods of estimating grapevine water status (predawn ψ, stem ψ, and leaf ψ) in Chardonnay and Cabernet-Sauvignon were satisfactory, since they correlated well with the amount of applied water and leaf gas exchange parameters, which is in agreement with the present results (Figures 2, 3A to C). Hsiao (1973) defined mild plant water stress for leaf ψ between -1.0 and -1.5 MPa, and severe water stress for leaf ψ below -1.5 MPa. According to his classification, the vines were not under severe water stress, even in 2007 when precipitation was very low. This finding might be partially explained by the type of soil that had a moderate to high water-holding capacity.

Species and cultivars with isohydric behaviour are able to maintain a tight control on leaf Ψ over a range of environmental conditions, while leaf ψ in anisohydric plants oscillates in response to environmental changes (Tardieu and Simonneau, 1998). Anisohydric plants typically exhibit less stomatal control over evaporative demand and soil moisture, allowing large fluctuations in leaf ψ (Franks *et al.,* 2007; Prieto *et al.,* 2010). Despite behaving as anisohydric plants, Cabernet-Sauvignon grapevines did not show strong anisohydric behaviour under experimental conditions in any of the years studied. Stomata regulate transpiration in order to gain sufficient carbon while leaf ψ is prevented from becoming too negative and breaking-down the hydraulic system of plants (Schultz and Matthews, 1997). This suggests that under specific climatic conditions and soil moisture, soil water status might not give an accurate measure of the leaf ψ.

5. Shoot growth and vine size

In 2006, the shoot growth rate decreased in RDI and control treatments (Figure 5A). The 100ET treatment showed an upward trend until the end of July and steadily decreased thereafter, as in all treatments. The growth rate in the PRD treatment decreased between

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the first and second sampling date, followed by a flat rate between the second and third reading, and ending with a downward trend (Figure 5A). This indicates that PRD treatment had enough soil moisture to sustain shoot growth compared to RDI treatments, which had a downward trend throughout the season. Despite higher growth rate than the control, the RDI treatments followed the same downward trend as the control. Although the same amount of water was applied in both treatments, a lower growth rate in PRD than in the 100ET treatment could be supported by the hormonal theory behind the PRD irrigation strategy (Dry and Loveys, 1998). In 2007, the growth pattern was different compared to 2006. The PRD treatment had lower or the same growth rate as the RDI treatments (Figure 5B). The RDI treatments had a steadily downward trend. In the control and PRD treatments, the growth rate decreased in the middle of July, then the trend increased to the end of July followed by a downward trend. The highest growth rate was found in the 100ET treatment. The highest magnitude among treatments was found at the end of July and beginning of August. On the last sampling date, the 100ET treatment still had a high growth rate compared to the other treatments (Figure 5B), which suggests that high water status has a negative impact on the canopy size even in dry years. In 2008, the shoot growth rate showed a different pattern than in 2006 and 2007, which reflected the very wet weather conditions for this particular year (Figure 5C). Treatments were not different on any of the three sampling dates. An interesting observation in 2008 was that the shoot growth rate was lower in the 100ET treatment compared to 2007. This could indicate that soil moisture is not the only factor that affects the vine vigour. Lower temperature and solar radiation could affect the carbon assimilation process and carbohydrate distribution in grapevines.

Growth is extremely sensitive to water stress. Schultz and Matthews (1988) reported that growth of Riesling shoots ceased at midday $\psi \leq -1.2$ MPa. In the present study, the lowest leaf ψ value was found in control in 2007 season (~ -1.4 MPa), which would have put leaf ψ well below the "stop-growth" threshold (Williams and Araujo, 2002). However, this was not the case in the present study, which could suggest that different grapevine cultivars have different capacity to cope with drought. Others suggested that controlling shoot growth by soil water status involves transfer of chemical information from roots to shoots via xylem (Davies *et al.,* 1997). This type of control of both shoot growth rate and gas exchange has been termed 'non-hydraulic' or 'chemical' signalling to distinguish it from 'hydraulic' signalling, which represents the transmission of reduced soil water availability via

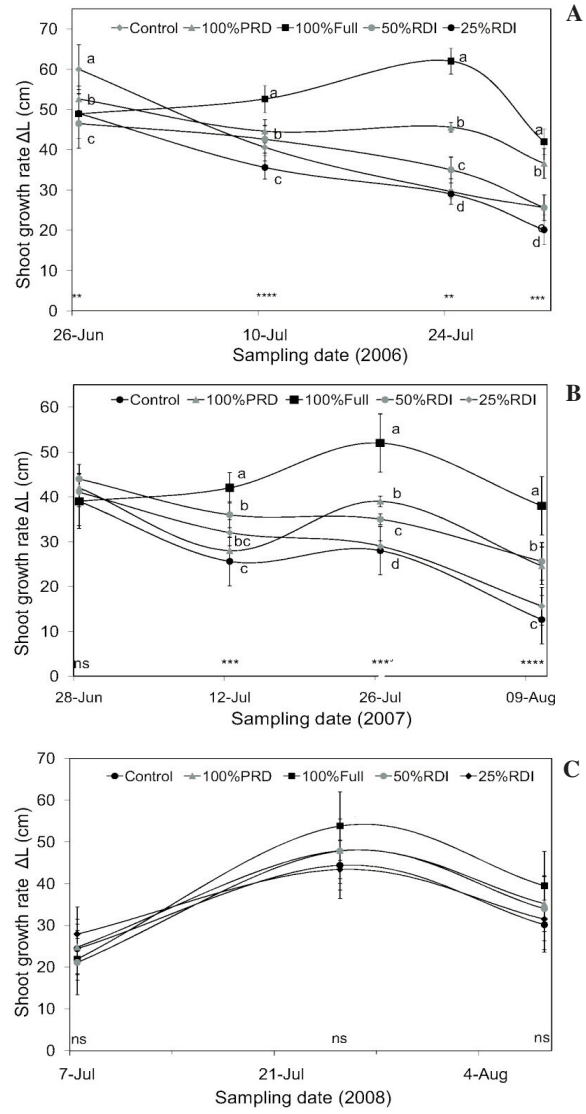


Figure 5. Impact of irrigation treatments on shoot growth rate of Cabernet-Sauvignon grapevines, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006 (A), 2007 (B) and 2008 (C).

Control (non-irrigated); PRD - partial root zone drying (100 % ETc); Full - conventional drip irrigation (100 % ETc); RDI - regulated deficit irrigation (25 and 50 % ETc); 25, 50, 100 % are the percentages of water replaced in the soil. **, ***, ****, ns: Significant at $p < 0.01$, 0.001, 0.0001, or not significant, respectively. Letters represent means separated at $p < 0.05$, Duncan's multiple range test.

changes in xylem sap tension (Dodd *et al.,* 1996). Studies on woody species showed that drying half of the root system typically resulted in reductions of shoot growth in the range of 10-25 %, relative to control plants (with both containers watered) following several weeks of treatment (Turner *et al.,* 1996). These findings could also support the data from the PRD treatment.

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Overall, the PRD treatment consistently had a higher growth rate than the RDI treatments during the most active growing period, and a lower rate than the 100ET treatment. Although the same amount of water was applied in both treatments, a lower growth rate in PRD than in the 100ET treatment could be supported by the hormonal theory behind the PRD irrigation strategy (Dry and Loveys, 1998). The results suggest that the ABA produced in the dry roots of vines from PRD treatment had a lower effect on shoot growth rate due to a dilution effect or perhaps due to other hormonal interactions or factors which control the activity of the apical tissue (Davies *et al.,* 2000). This is in contradiction with what most of the studies on PRD treatment reported. This could be explained by the amount of water supplied in our PRD treatments. However, our data is partially supported by findings of Gu *et al.* (2004), who concluded that the effect of PRD treatment was determine by the water deficit applied and not by the irrigation strategy used.

Vine size. Lack of correlation between vine size and shoot growth rate could be explained by different partitioning of the dry matter under different water deficit levels (Williams and Grimes, 1987). Our results (Table 2) are in contradiction with those found by Williams *et al.* (2010), who showed that Thompson Seedless pruning weights were a linear function of applied water amounts. The lack of correlation between shoot growth and pruning weights could also be explained by the fact that radial shoot growth is less affected by water deficits than apical growth (Williams and Matthews, 1990). Moreover, this lack of relationship could also be explained by the competition between the reproductive and vegetative apparatus, since the data showed that irrigation treatments affected both crop load and yield.

6. Yield components

The plots were harvested by the grower in 2006 prior to any yield data collection. In 2007, yield was different compared to control in all treatments (Table 2). The highest yield was observed in the 100ET treatment (6.32 kg/vine). However, PRD treatment had yields between those found in the RDI and 100ET treatments. The highest number of clusters per vine was observed in PRD treatment, perhaps due to a balance reached between vegetative and reproductive apparatus in the previous year. As expected, both the control and 100ET treatments had lower number of clusters than PRD and RDI treatments. Since cluster initiation occurred in the previous season, the differentiation process is likely to be affected by the canopy size in the 100ET treatment or competition for carbohydrates in the control. Overall, all irrigated treatments had heavier clusters than control. The 100ET treatment had the highest yield because of both high numbers of berries per cluster and berry weight. Berry weight increased

Table 2. Impact of irrigation treatments on yield components and vine size of Cabernet-Sauvignon grapevines, Lambert Vineyards, Niagara-on-the-Lake, ON, 2007-2008

Treatment	Vine size (kg/vine)	Yield (kg/vine)	Clusters/vine	Cluster wt. (g)	Berries/cluster	Berry wt. (g)
2007						
Control	0.35 c	3.52 c	41 b	85.9 c	100 b	1.13 c
PRD	0.37 c	**4.91 ab**	**48 a**	**102.9 ab**	105 ab	**1.26 b**
Full	**0.48 a**	**6.32 a**	39 b	**162.9 a**	**116 a**	**1.33 a**
50 RDI	**0.44 b**	**4.29 b**	43 ab	**99.7 ab**	**89 c**	**1.28 ab**
25 RDI	0.35c	**4.40 b**	45 ab	**97.7 ab**	98 b	**1.29 ab**
Significance	**	****	***	****	*	*
2008						
Control	0,49	5.61 b	42 b	133.5 c	93 c	1.36 b
PRD	0,51	6.5 ab	44 b	147.7 ab	**109 b**	1.41ab
Full	0,53	**6.60 a**	**49 a**	134.6 c	**116 a**	**1.43 a**
50 RDI	0,5	6.38 ab	46 ab	138.7 b	**110 b**	1.41 ab
25 RDI	0,49	6.25 ab	42 b	148.8 a	100 bc	1.39 ab
Significance	ns	*	*	*	*	*

Control (non-irrigated); PRD - partial root zone drying (100 % ET_c); Full - conventional drip irrigation (100 % ET_c); RDI - regulated deficit irrigation (25 and 50 % ET_c); 25, 50, 100 % are the percentages of water replaced in the soil.
*, **, ***, ****, 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, Dunnett's t-test; boldfaced and underlined data are significantly less than the control.

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in irrigated treatments compared to the control treatments. In 2008, yield in the control was different only from the 100ET treatment, which had the highest number of clusters. This could also be explained by weather conditions from previous year. Since 2007 season was the driest and hottest from the period studied, it seems that replacing 100 % ET_c had a positive effect on cluster differentiation. However, the cluster weight and the number of berries per cluster were not well explained by the irrigation treatments in 2008 (Table 2).

Water deficits have decreased yield through their effect not only on cluster initiation and differentiation, but also on berry set and growth (Hardie and Considine, 1976 ; Matthews and Anderson, 1989). These findings were in agreement with our results only from 2007 and not from 2008. PRD can cause a smaller reduction in berry weight and yield, within a range lower than that reported in the current study (Dry *et al.,* 2000 a, b). However, studies on water deficit strategies in field-grown experimental grapevines (Stoll *et al.,* 2000), potted vines (Antolín *et al.,* 2006) and commercial trials (Dry *et al.,* 2000 a, b) showed no change in berry size or yield as a result of PRD strategy. Overall, in 2007, the number of clusters was higher in vines under some level of water deficit compared to full irrigated vines, with an opposite pattern in 2008. Irrigation could affect the weight of berries both directly and indirectly (Esteban *et al.,* 1999). The direct effect is materialized in a large number of cells (when there is no water restrictions during stage I of fruit growth) or by a larger cell size (when there is no water restriction during stage III) (Matthews and Anderson, 1989 ; Bravdo and Naor, 1996). Nevertheless, Ojeda *et al.* (2001) by quantifying the DNA from pericarp during the phase I of berry development showed that water stress does not affect berry weight through the cell division rate but rather it modifies the structural properties of the cell components and consequently cell wall extensibility, thereby limiting the subsequent enlargement of pericarp cells.

Table 3. Impact of irrigation treatments on berry composition of Cabernet-Sauvignon grapevines, Lambert Vineyards, Niagara-on-the-Lake, ON, 2006-2008.

Treatment	°Brix	TA (g/L)	pH	A520 (AU)	Anthocyanins (mg/L)	Total phenols (mg/L)
2006						
Control	21.7 a	6.8 b	3.82 b	6.60 c	413.4 b	2300 b
PRD	21.3 ab	7.5 ab	3.81 b	6.61 c	439.4 ab	**2146 c**
Full	**21.1 b**	**7.8 a**	**3.85 a**	**7.67 ab**	**401.6 c**	2234 bc
50 RDI	**20.9 b**	7.0 b	3.84 ab	**7.11 b**	435.2 ab	**2486 a**
25 RDI	21.6 ab	7.0 b	3.82 b	**7.90 a**	**449.0 a**	2454 ab
Significance	****	****	****	***	**	****
2007						
Control	23.2 a	7.1 b	3.63 b	8.20 b	839 b	2301 b
PRD	**22.6 b**	7.4 ab	**3.49 c**	7.60 ab	820 bc	2402 ab
Full	**21.8 c**	**7.8 a**	**3.73 a**	**7.11 c**	**659 c**	**1761 c**
50 RDI	23.0 a	7.0 b	3.69 ab	**8.56 a**	860 ab	1982 bc
25 RDI	23.3 a	6.9 b	3.67 ab	**8.46 a**	**871 a**	**2456 a**
Significance	****	****	***	****	**	****
2008						
Control	20	10.3 a	3.66 b	6.39 a	438 a	1560 a
PRD	19,9	9.7 ab	**3.69 a**	5.99 ab	421 ab	1523 ab
Full	19,7	10.2 ab	3.68 ab	**5.81 b**	**396 b**	**1321 b**
50 RDI	20	**9.2 b**	3.65 b	6.31 ab	415 ab	1489 ab
25 RDI	19,9	10.3 ab	3.66 b	6.21 ab	426 ab	1509 ab
Significance	ns	*	*	*	*	*

Control (non-irrigated) ; PRD - partial root zone drying (100 % ET_c) ; Full - conventional drip irrigation (100 % ET_c) ; RDI - regulated deficit irrigation (25 and 50 % ET_c) ; 25, 50, 100 % are the percentages of water replaced in the soil.
*, **, ***, ****, 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, Dunnett's t-test ; boldfaced and underlined data are significantly less than the control.

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7. Berry composition

In 2006, all irrigated treatments reduced °Brix compared to the control (Table 3). However, the 25ET RDI was just slightly lower than the control. In 2007, PRD slightly reduced °Brix while 25ET RDI increased it compared to the control. The lowest °Brix was found in the 100ET treatment. In 2008, the control and 50 % RDI tended to have higher °Brix than the other treatments. However, no differences were found between treatments. TA increased slightly in all treatments in 2006, and only 100ET vines were higher than the control (Table 3). Except for the PRD and 100ET treatments, which slightly increased TA, all means were lower in 2007. TA was higher in 2008 compared to the other years. This could have been an effect of the delay in fruit maturation due to low temperatures and solar radiation. Berry TA was slightly lower in PRD and 50 % RDI. Berry pH increased slightly in the 100ET and 50ET RDI treatments in 2006, and not in PRD (Table 3). In 2007, all treatments except for PRD increased in pH compared to the control, while in 2008, the 100ET and PRD treatments had highest pH.

Berry pH increased linearly with berry ripening while TA decreased exponentially (Esteban *et al.,* 2002). The increase of must TA is a common response to irrigation (Williams and Matthews, 1990), and it is considered beneficial for wines produced in hot areas, as they usually are low in TA. Interestingly, increased juice pH and decreased juice TA were observed in response to the PRD treatment in 2008 and not in 2007. This observation most likely indicates a water-deficit-induced decrease in total acidity, which is known to result primarily from an accelerated decrease in malic acid during berry ripening under these conditions (Esteban *et al.,* 1999). However, contradictory results regarding the effect of water deficit on pH and TA of grapes were found in previous studies (Antolín *et al.,* 2006, Bindon *et al.,* 2007).

Absorbance at 520 nm increased more in the 100ET and 25ET RDI than in the other treatments in 2006 (Table 3). In 2007, A_{520} was higher in all treatments compared to 2006. However, in 2007, A_{520} increased only in RDI treatments, and decreased in others compared to the control. The 100ET treatment had lowest A_{520} in 2008. Anthocyanins were lowest in the 100ET treatment and highest in 25ET RDI in 2006 (Table 3). However, all irrigated treatments had higher anthocyanins contents than the control, except for the 100ET treatment. The RDI treatments increased anthocyanins compared to the control in 2007, while the PRD and 100ET treatments were lower. RDI treatments had higher total phenols than the control in 2006, while PRD and 100ET treatments had lower phenols than the control (Table 3). Total phenols were higher in PRD and 25ET RDI in 2007, and lower in 100ET and 50 % RDI when compared to control. The 100ET treatment reduced both anthocyanins and total phenols in 2008. Overall, vintage had a substantial effect on fruit composition—anthocyanins and phenols varied between 100 and 130 % from vintage to vintage and just 5 to 40 % due to irrigation treatments (Table 3).

The primary mechanism by which water deficits increased the concentrations of skin tannin and anthocyanins is probably the differential growth responses of skin and inner mesocarp tissue to water deficits (Roby and Matthews, 2004), although it could be a direct stimulation of their biosynthesis by water deficit (Roby *et al.,* 2004). Solar heating of grape berries could increase cellular respiration and water loss, and both heat and light could affect the accumulation of anthocyanins and other phenolic compounds (Mori *et al.,* 2007). Hardie and Considine (1976) reported a decreased colour with water deficits, and in most cases the fruit with low colour was harvested at lower ºBrix than the control. Furthermore, one study indicated that the effect of vine water status on anthocyanin concentration for each berry size was higher than the effect of fruit size (Roby *et al.,* 2004). Spayd *et al.* (2002) found that higher temperature and incident light values measured during ripening increased anthocyanins and total phenols in PRD treatment compared to fully irrigated or deficit irrigation. In contrast, Keller and Hrazdina (1998) showed that for Cabernet-Sauvignon, the anthocyanin concentration in berries was similar at 20 % and 100 % sunlight interception, which suggests that canopy size due to irrigation treatments could not have any effect on anthocyanin accumulation. Downey *et al.* (2004) showed that vine vigour and light exposure have the most significant impact on tannin accumulation.

Mori *et al.* (2007) showed that the response of different anthocyanin types was variable, with malvidin-glucosides being more resistant to degradation under elevated temperature than non-malvidin derivatives of which degradation was enhanced. Moreover, PRD treatments can cause an increase in delphinidin-based anthocyanins, indicating a possible shift in the regulation of the anthocyanin pathway (Boss *et al.,* 1996). They argued that the shift in the anthocyanin profile towards non-malvidin anthocyanins is due to methyltransferase enzyme resulting in a relative decrease in the proportion of methoxylated anthocyanins. Visual

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observations did not indicate an obvious change in the hue colour, which could suggest no shift among different anthocyanins due to irrigation treatments. However, this possibility was not excluded since small changes between different anthocyanins are not necessarily reflected in changes in hue colour. In our trials, anthocyanins and total phenols varied substantially from season to season. There was no linear relationship between anthocyanins and total phenols, or a consistent pattern from year to year, which suggests that besides soil water status, other factors could affect phenolic biosynthesis. However, RDI and PRD treatments showed a positive effect under particular weather conditions.

8. Must and wine composition

Must and wine composition data were collected only for 2007 vintage. In this dry and hot year, non-irrigated vines did not accumulate more °Brix than treatments under water deficits (Table 4). The 25ET RDI treatment had higher °Brix compared to other treatments. PRD had slightly lower °Brix than the control. Alternating the wet zone on each half of the root system but still with full replacement of water lost through evapotranspiration did not improve the must and wine quality. A likely explanation is that berry composition is diluted by the high amount of water used through irrigation. Must TA was lowest in control, while the irrigated treatments were higher but close to each other (Table 4). Must pH showed the highest magnitude difference among the treatments. The 25ET RDI had the lowest pH value in the must while the 100ET the highest (Table 4). In 2007, the wine composition of the irrigated treatments had almost the same pattern as that from the must composition (Table 4). The control had the highest ethanol concentration while wine from 100ET vines was the lowest. Wine pH was lowest in the PRD wines, while in the other treatments the pH was higher but close to each other. TA was the highest in the wines from the 100ET treatment. Total anthocyanin concentration was highly affected by irrigation treatments. The 100ET treatment had the lowest anthocyanin and phenol concentrations (Table 4).

A pH > 3.60 is normally not a positive characteristic in must and wine since it increases the activity of spoilage microorganisms, lowers the colour intensity of red wines, binds more SO_2 and reduces free SO_2, and adversely affects the ability of wine to age (de la Hera-Orts *et al.*, 2005). Trials investigating the effects of PRD on Cabernet-Sauvignon showed higher wine colour density and red pigment coloration in PRD wines after 6 months of ageing

Table 4. Impact of irrigation treatments on must and wine composition of Cabernet-Sauvignon, Lambert Vineyards, Niagara-on-the-Lake, ON, 2007.

Must composition 2007			
Treatment	**Brix**	**Titratable acidity(g/L)**	**pH**
Control	22.2 b	8.3 b	3.46 b
PRD	21.4 c	9.1 ab	3.56 ab
Full	21.1 c	**9.3 a**	**3.60 a**
50 RDI	22.1 b	9.1 ab	3.49 b
25 RDI	**22.4 a**	9.0 ab	3.36 c
Significance	*	***	**

Wine composition 2007						
Treatment	**EtOH% (v/v)**	**TA (g/L)**	**pH**	**Hue (OD420/520)**	**Anthocyanins (mg/L)**	**Phenols (mg/L)**
Control	12.31 a	5.1 b	3.59 b	0.68 a	759 a	2211 a
PRD	**11.72 b**	5.6 ab	**3.46 c**	0.64 ab	**711 b**	**1952 b**
Full	**11.65 b**	**5.8 a**	**3.67 a**	**0.60 b**	**546 c**	**1631 c**
50 RDI	11.96 ab	5.5 ab	**3.65 a**	0.63 ab	**638 bc**	**1860 bc**
25 RDI	12.16 ab	5.3 b	**3.64 a**	0.65 ab	**727 b**	**2076 b**
Significance	*	*	*	*	**	***

Control (non-irrigated); PRD - partial root zone drying (100 % ET_c); Full - conventional drip irrigation (100 % ET_c); RDI - regulated deficit irrigation (25 and 50 % ET_c); 25, 50, 100 % are the percentages of water replaced in the soil.
*, **, ***, ****, 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, Dunnett's t-test; boldfaced and underlined data are significantly less than the control.

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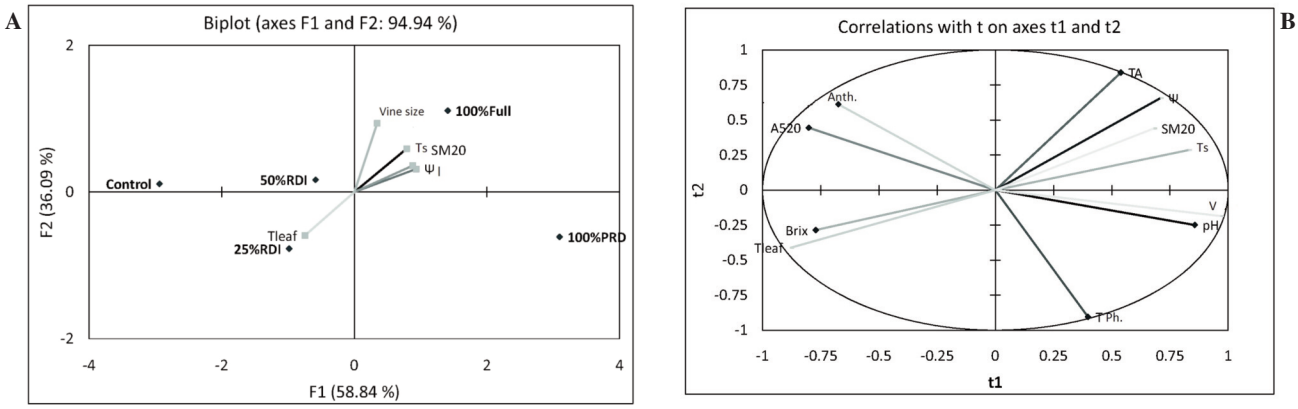


Figure 6. (A) Principal component analysis (F1&F2) of soil water status and vine water status means from five irrigation treatments of Cabernet-Sauvignon grapevines from Lambert Vineyards, Niagara-on-the-Lake, ON, 2006. (B) PLS regression analysis of soil and plant water status and berry composition data from five irrigation treatments of Cabernet-Sauvignon grapevines.

Legend (both A and B): Control (non-irrigated); PRD - partial root zone drying (100 % ETc); Full - conventional drip irrigation (100 % ETc); RDI - regulated deficit irrigation (25 and 50 % ETc); Tleaf - leaf temperature; SM20 - soil moisture at 20 cm depth; ψ - leaf water potential; Ts - transpiration. B only: TA - titratable acidity; A520 - absorbance at 520 nm; V - vine size; Anth. - anthocyanins; TPh. - total phenols.

(Bindon *et al.*, 2008). They suggested that the increase in red pigments of the PRD wines was caused by an increase in co-pigmented or polymeric forms of the anthocyanins, rather than a change in anthocyanin concentration alone. This is consistent with other work suggesting that increases in red wine colour could be caused by a change in chemical properties of the anthocyanins to polymeric forms during the winemaking or ageing process (Levengood and Boulton, 2004). Since aged wine composition was not measured, we do not exclude the possibility that deficit irrigation could have a beneficial effect on colour stability during the ageing process.

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

2006. The PCA of field data indicated that factor 1 (F1) and factor 2 (F2) explained 94.9 % of the variability in the data set (Figure 6A). Soil moisture was highly positively correlated with Ts rate and leaf ψ, and negatively correlated with leaf temperature. Vine size showed less correlation with soil moisture. The irrigated treatments were well separated, with the highest variation in terms of soil and vine water status among the control, 100ET and PRD treatments. The PLS regression performed on field and berry composition data illustrated a strong positive relationship between °Brix and leaf temperature, and negative correlation with leaf ψ, Ts and soil moisture (Figure 6B). Vine size showed a strong positive correlation with juice pH, and negative correlation with anthocyanins. This confirms the negative effects of dense canopies on anthocyanins due to poor microclimate in the fruit zone.

2007. The PCA plot of field data indicated that PC1 and PC2 explained 93.1 % of the variability in the data set (Figure 7A). F1 explained 83.9 % of the variability, while F2 explained an additional 9.3 %. F1 was positively loaded with leaf ψ, and negatively loaded with leaf temperature. F2 was positively loaded with vine size. The PCA pattern was different than in 2006, showing different relationships among field variables, which could be explained mostly by different weather patterns. The PCA plot showed a better discrimination among treatments in 2007 compared to 2006. The PRD treatment was highly associated with Ts and soil moisture. Control and 25ET RDI were located on the left side of the plot and highly associated with the leaf temperature. All other irrigated treatments were located on the right side of the plot. Soil and plant water status showed a better relationship in the PRD and RDI than in the 100ET treatment. PCA was also performed on vine water status, yield component and berry composition data in 2007. The PCA diagram indicated that F1 and F2 explained 83.9 % of the variability (Figure 7B). F1 explained 63.0 % while F2 explained an additional 20.9 % of the variability. F1 was heavy loaded with leaf ψ, yield and cluster weight, and negatively loaded with leaf temperature and °Brix. F2 was positively loaded with TA and cluster number, and negatively with juice pH. Phenols and anthocyanins were negatively correlated with vine

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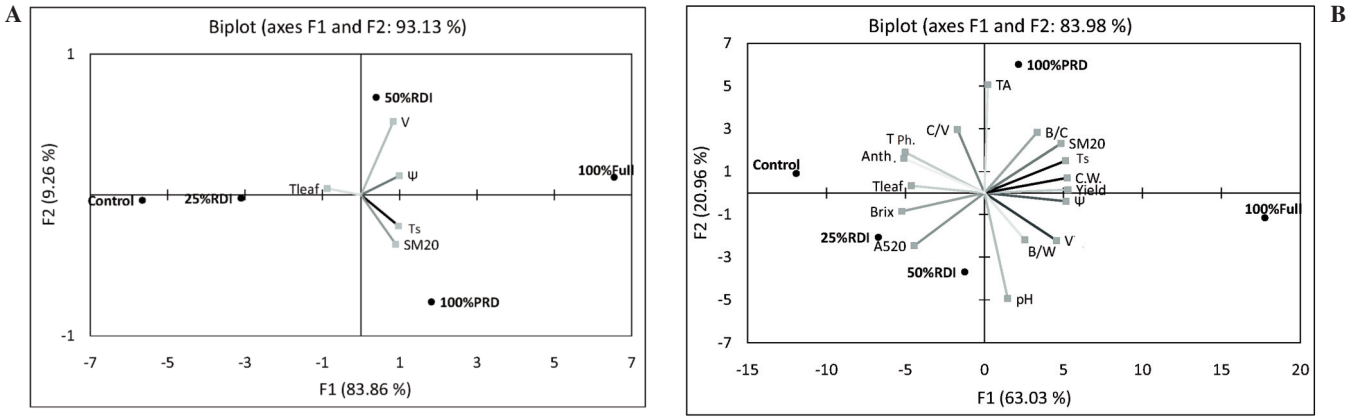


Figure 7. (A) Principal component analysis (F1&F2) of soil water status and physiological data means from five irrigation treatments of Cabernet-Sauvignon grapevines from Lambert Vineyards, Niagara-on-the-Lake, ON, 2007. (B) Principal component analysis (F1&F2) of soil water status, vine water status, yield component and berry composition means from five irrigation treatments of Cabernet-Sauvignon grapevines from Lambert Vineyards, 2007.

Legend (both A and B): Control (non-irrigated); PRD - partial root zone drying (100 % ETc); Full - conventional drip irrigation (100 % ETc); RDI - regulated deficit irrigation (25 and 50 % ETc); V - vine size; Tleaf - leaf temperature; SM20 - soil moisture at 20 cm depth; ψ - leaf water potential; Ts - transpiration. B only: C/V - clusters per vine; C.W. - cluster weight; B/C - berries per cluster; B/W - berry weight; TA - titratable acidity; A520 - absorbance at 520 nm; Anth. - anthocyanins; TPh. - total phenols.

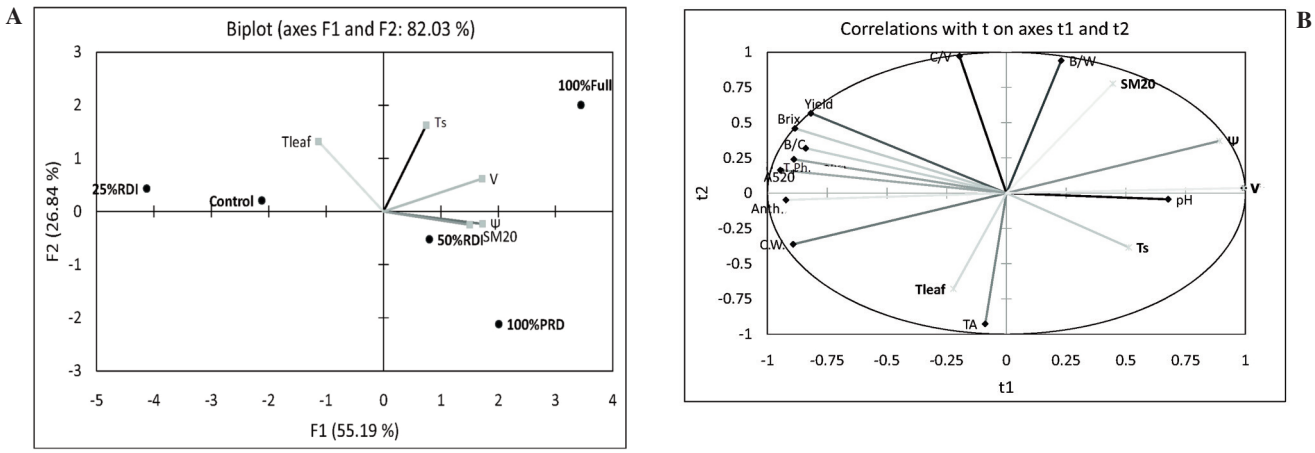


Figure 8. (A) Principal component analysis (F1&F2) of soil and vine water status from five irrigation treatments of Cabernet-Sauvignon grapevines from Lambert Vineyards, Niagara-on-the-Lake, ON, 2008. (B) PLS regression analysis of soil and vine water status, yield component and berry composition data from five irrigation treatments of Cabernet Sauvignon grapevines from Lambert Vineyards, 2008.

Legend (both A and B): Control (non-irrigated); PRD - partial root zone drying (100 % ETc); Full - conventional drip irrigation (100 % ETc); RDI - regulated deficit irrigation (25 and 50 % ETc); Tleaf - leaf temperature; SM20 - soil moisture at 20 cm depth; ψ - leaf water potential; Ts - transpiration; B only: C/V - clusters per vine; C.W. - cluster weight; B/C - berries per cluster; B/W - berry weight; TA - titratable acidity; A520 - absorbance at 520 nm; Anth. - anthocyanins; TPh. - total phenols.

size while clusters per vine were negatively correlated with berry weight and juice pH. °Brix was negatively correlated with berries per cluster, soil moisture, cluster weight and yield. The control and RDI treatments were located on the left side of the plot, being highly associated with higher °Brix, phenols and anthocyanins.

2008. The PCA plot of soil and plant water status data indicated that PC1 and PC2 explained 82.0 % of the variability in the data set (Figure 8A). Vine size, leaf ψ and soil moisture was positively loaded on F1 while Ts was positively loaded on F2. Leaf temperature data did not well explain the variability on F1 and F2. Control and RDI (25ET) were grouped on the upper left plane of the plot, fully irrigated in the upper right plane, while PRD and RDI (50ET) were on the lower right plane. PLS regression was also performed on field, yield component and berry composition data in 2008 (Figure 8B). PLS illustrated strong positive correlations between vine size and juice pH, and negative correlations with total

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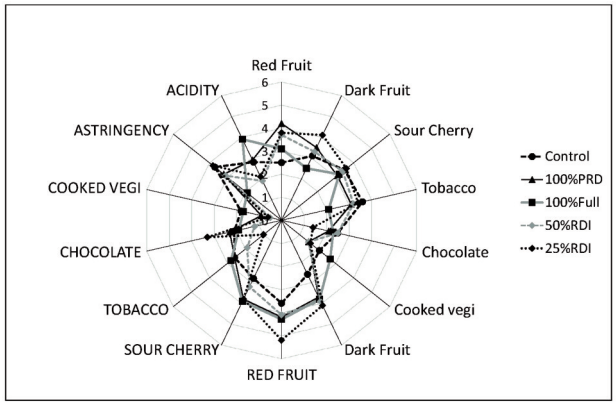


Figure 9. Radar diagram of mean intensity ratings of five Cabernet-Sauvignon wines made from different irrigation treatments, Lambert Vineyards, Niagara-on-the-Lake, ON, 2007. Aroma and flavour attributes are specified by lower and higher case letters, respectively.

Legend: Control (non-irrigated); PRD - partial root zone drying (100 % ETc); Full - conventional drip irrigation (100 % ETc); RDI - regulated deficit irrigation (25 and 50 % ETc); 25, 50, 100 % are the percentages of water replaced in the soil.

phenols, anthocyanins and berries per cluster. Ts rate was negatively correlated with yield, berries per cluster and °Brix. Soil moisture was highly positively correlated with berry weight, and negatively with leaf temperature and TA. No strong relationship was observed between soil moisture and other variables.

10. Sensory analysis

From the entire period studied only wines from 2007 were subjected to sensory evaluation. This season was characterized as the hottest and driest from the period studied. The 2007 vintage was assessed for seven aroma descriptors and nine flavour and mouthfeel descriptors. Data showed differences in the sensory profiles of wines made from vines under different levels of water status (Table 5, Figure 9). The control had the highest scores for tobacco aroma, chocolate and cooked vegetable flavour while for a few attributes it had lower or the same intensity as the 25RDI. The control did not have highest scores for the fruity attributes. The 100ET treatment had highest scores for vegetal aroma, sour cherry, acidity (sourness), astringency, and tobacco flavour. PRD wines had a higher score than the other treatments only for red fruit aroma and chocolate flavour while most of the attributes were lower than other treatments. Deficit treatments, especially 25 RDI, showed consistently high scores for most of the positive sensory characteristics in Cabernet wines. Despite applying the same amount of water in full and PRD treatments, the sensory profile varied between these treatments. The PRD treatments did not show the negative attributes as extreme acidity and vegetal characters, but had better scores than the control and 100ET treatments for some typical descriptors for Cabernet-Sauvignon wines. The

Table 5. Comparison of mean sensory scores among Cabernet-Sauvignon wines based on five irrigation treatments, Niagara Peninsula of Ontario, 2007

Treatment	Control	PRD	Full	50 RDI	25 RDI	Pr>F
Aroma						
Red fruit	2.5 c	4.2 a	3.1 b	3.7 ab	3.8 ab	0,0001
Dark fruit	3.1 b	3.5 ab	2.5 c	3.3 b	4.1 a	0,008
Sour cherry	3.5 ab	3.1 b	3.2 b	3.4 ab	3.6 a	0,042
Tobacco aroma	3.6 a	3.1 b	2.1 c	3.2 b	3.4 ab	0,053
Chocolate	2.5 a	2.1 b	2.3 ab	2.5 a	1.4 c	0,009
Cooked vegetable	2.1 b	1.5 c	2.7 a	1.5 c	1.6 c	0,006
Flavour						
Red fruit	3.6 c	4.2 ab	4.3 ab	4.1 b	5.2 a	0,0001
Dark fruit	2.6 b	3.7 ab	3.8 ab	3.9 ab	4.1 a	0,002
Sour cherry	2.8 c	3.8 ab	3.9 a	3.2 b	3.8 ab	0,021
Tobacco	1.6 bc	2.6 ab	2.8 a	1.9 b	1.1 c	0,005
Chocolate	2.1 ab	2.3 a	1.9 ab	1.2 b	1.3 b	0,041
Cooked vegetable	1.8 a	0.9 b	0.7 b	0.5 b	0.6 b	0,018
Astringency	2.9 b	3.2 b	3.9 a	3.1 b	2.8 b	0,004
Acidity	2.8 b	2.9 b	3.9 a	1.9 c	2.1 c	0,0001

Control (non-irrigated); PRD - partial root zone drying (100 % ET_c); Full - conventional drip irrigation (100 % ET_c); RDI - regulated deficit irrigation (25 and 50 % ET_c); 25, 50, 100 % are the percentages of water replaced in the soil.
Means in the rows with different letters represent means separated at $p < 0.05$, Duncan's multiple range test.

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highest magnitude among treatments was found for red fruit, chocolate, tobacco, astringency and acidity attributes.

The PCA on the 2007 sensory data showed that the F1 and F2 explained 78.6 % of the variability (Figure 10A). F1 explained 50.1 % while F2 explained an additional 28.6 %. F1 was positively loaded with dark fruit aroma and chocolate flavour, and negatively loaded with tobacco and cooked vegetal flavour, cooked vegetal and chocolate aroma. F2 was positively loaded with sour cherry flavour. The distribution of wines on the PCA plot showed good separation between treatments. The 100ET treatment was located on the upper left plane and associated mostly with acidity and cooked vegetal flavour descriptors while the control was located on the lower left plane and associated with chocolate and cooked vegetal aromas. PRD and RDI treatments were located on the right side and were associated with the most descriptors desired for a typical sensory profile of Cabernet-Sauvignon wines. Despite having just one vintage for sensory evaluation, data clearly showed that in dry and hot years, neither full water replacement in the soil nor control treatment had a positive effect on the wine sensory profile. A PLS regression was also performed on the full data set in 2007 (Figure 10B). PLS illustrated a high degree of correlation among soil moisture, vigour, Ts rate, yield, phenols, anthocyanins, and ethanol. Dark fruit, chocolate and clusters per vine were positively correlated to each other and negatively correlated with cooked vegetal, tobacco and acidity. Red and dark fruit aromas were negatively correlated with leaf temperature, which could suggest that leaf temperature might control different enzymatic reactions related to aroma precursor synthesis.

Vegetal aromas such as bell pepper or asparagus contribute to the distinctive varietal aromas of Cabernet-Sauvignon, Merlot and Sauvignon blanc wines. However, at high level, these vegetal notes could be considered undesirable. The bell pepper aroma in Cabernet-Sauvignon wines has been correlated with the concentration of 3-isobutyl-2-methoxypyrazine (IBMP) (Chapman *et al.,* 2004). IBMP concentrations and bell pepper aroma decreased when light exposure or temperature increased (Roujou de Boubée *et al.,* 2000). The term "vegetal" can also be applied to some other aroma notes like asparagus and cooked vegetable produced by thiol compounds (Tominaga *et al.*, 1998). This could explain easily why the panellists were not able to make a clear distinction between green pepper and asparagus aroma, and preferred to use the cooked vegetal attribute in describing these Cabernet-Sauvignon wines. Since the low precipitation was accompanied by high temperature and solar radiation in 2007, this could be a reasonable explanation for the low vegetal and high fruity characteristics in the RDI treatments.

Light and temperature control the norisoprenoid concentrations, which are directly correlated with the high concentrations of carotenoids in grapes under moderate water stress (Lee *et al.,* 2007; Oliveira *et*

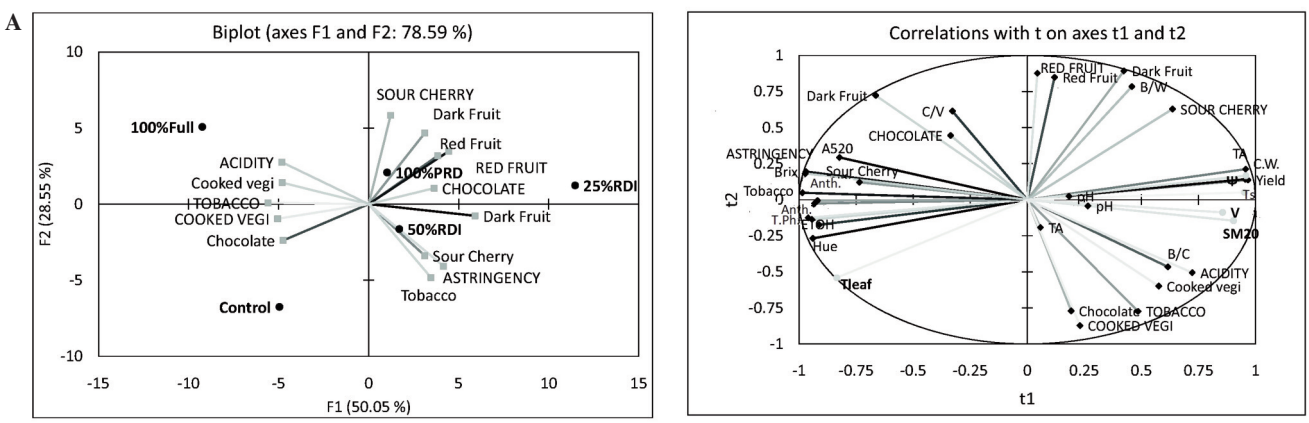


Figure 10. (A) Principal component analysis (F1&F2) of sensory data means from five irrigation treatments of Cabernet-Sauvignon grapevines from Lambert Vineyards, Niagara-on-the-Lake, ON, 2007. (B) PLS regression analysis of soil and plant water status, yield components, berry and wine composition and sensory data from five irrigation treatments of Cabernet-Sauvignon grapevines from Lambert Vineyards, 2007.

(both A and B): Control (non-irrigated); PRD - partial root zone drying (100 % ETc); Full - conventional drip irrigation (100 % ETc); RDI - regulated deficit irrigation (25 and 50 % ETc); B only: Tleaf - leaf temperature; SM20 - soil moisture at 20 cm depth; ψ - 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; EtOH - ethanol; TA - titratable acidity; A520 - absorbance at 520 nm; Antho. - anthocyanins; T Ph .- total phenols.

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al., 2003). Studies comparing sun-exposed and shaded grape clusters showed that variation in the level of light incident on a grape cluster had an effect on berry carotenoids (Bindon *et al.,* 2007). Numerous studies showed that in grapevines with dense canopies, light and temperature conditions of the cluster zone were altered. In grapevines, water stress can indirectly affect the light environment of developing fruit, through a reduction in shoot growth rate and vine leaf area (Dry and Loveys, 1998). As a consequence, carotenoid synthesis and its breakdown could be affected, and thus precursors of the C_{13}-norisoprenoids are affected as well. However, water deficits in grapevines can elevate the level of carotenoids in grapes (Bindon *et al.,* 2007). The berry-derived carotenoids lutein, α-carotene, neoxanthin, violaxanthin, and luteoxanthin increased up to 60 % in a non-irrigated compared to an irrigated treatment only when the soil had a low water-holding capacity (Oliveira *et al.,* 2003). Moreover, in one irrigation trial on Cabernet-Sauvignon, a PRD treatment increased the carotenoid concentration as well as the C_{13}-norisoprenoids β-damascenone, β-ionone and 1,1,6-trimethyl-1,2-dihydronaphtalene relative to the control (both sides of the root system irrigated) (Bindon *et al.,* 2007). They found that this increase was unrelated to berry size or the altered surface area-to-volume ratio. This suggests that water status could have a great impact on the wine sensory profile through the concentration of the aroma volatiles.

The present data is partially supported by another study on effect of water status on Cabernet-Sauvignon sensory profile. Chapman *et al.* (2004) found in a standard irrigation treatment (32 L/vine/week) the highest ratings in vegetal aroma, bell pepper aroma, astringency, and bitterness while minimum irrigation (< -1.6 MPa) and double irrigation treatments (64 L/vine/week) had astringency much lower than in standard treatments. The same authors showed that minimum irrigation (water deficit treatment) led to the fruitiest wines, which is in agreement with our findings (Table 5). Fresh cherry, red/black berry, jam/cooked berry, and dried fruit/raisin aromas, as well as acidic and fruity by mouth were rated highest in the minimum irrigated treatments. This is in contradiction with most of the irrigation studies where irrigation showed to decrease acidity. However, double irrigated treatments had highest ratings for fresh cherry, which is in agreement with these findings in full irrigated treatments.

CONCLUSIONS

This study may be the first evaluation of PRD on a red winegrape cultivar in a cool, humid climate. RDI and PRD led to frequent improvements in berry composition. Increasing °Brix in non-irrigated vines did not necessarily lead to an improvement in wine quality because this process was due mostly to desiccation rather than improved water use efficiency. RDI strategies were more consistent, and had a greater magnitude of effect than PRD treatments in terms of vine water status, yield components, and fruit composition. Water depletion patterns in the soil showed that there was a high magnitude of difference between irrigation strategies in terms of vine water status (Ts, leaf ψ), soil moisture, yield components, and fruit composition in warm vs. cool years.

Despite improving vine performance, and in some cases grape composition, PRD is not recommended in this area due to high installation cost, and less efficacy than RDI treatments. However, more research should be conducted on PRD strategy to understand its lack of efficacy in humid regions. 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 localized effects of PRD. Nonetheless, in a related study with Sauvignon blanc on the same site, it was noteworthy that "wet" and "dry" zones were apparent, even in seasons such as 2006 where rainfall was frequent, and there is no reason to suggest that this did not occur in this study. Perhaps, by refining the PRD strategy and lowering the installation price, this could be a viable irrigation strategy for cool regions. Perhaps the results from PRD treatment did not lead to an obvious improvement in the majority of variables because 100 % of ET_c was replaced rather than a fraction of the ET_c.

There is no doubt about the positive effect of using RDI strategy in vineyards, especially in very hot and dry years. However, it is essential to carry out vineyard experiments on irrigation strategies in combination with other cultural practices if the ultimate objective is to manipulate wine sensory attributes through vineyard management. Moreover, if irrigation experiments are carried out in one vineyard, the trials should be extended over a longer period of time to have a better control of the root system. Moreover, even if irrigation is not recommended annually due to high weather variability, in hot and dry years, RDI strategies using drip irrigation are highly recommended to improve grape composition. However, more research should

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be done regarding the relationships between soil and vine water status, and their effect on the chemical compounds responsible for the sensory profile of this and other cultivars. Contrary to what many winemakers believe, the quality of Cabernet-Sauvignon wines can be improved by using RDI or PRD in warm and dry years in the Niagara Region.

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