Irrigation Scheduling for Sovereign Coronation Grapevines Based Upon Evapotranspiration Calculations and Crop Coefficients

By

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A Thesis submitted to the

Department of Biological Sciences

in partial fulfillment of the requirements

for the degree of Master of Science

May 2006

Brock University

St. Catharines, Ontario

Abstract

Several irrigation treatments were evaluated on Sovereign Coronation table grapes at two sites over a 3-year period in the cool humid Niagara Peninsula of Ontario. Trials were conducted in the Hipple (Beamsville, ON) and the Lambert Vineyards (Niagara-on-the-Lake, ON) in 2003 to 2005 with the objective of assessing the usefulness of the modified Penman-Monteith equation to accurately schedule vine irrigation needs. Data (relative humidity, windspeed, solar radiation, and temperature) required to precisely calculate evapotranspiration (ET_0) were downloaded from the Ontario Weather Network. One of two ET_0 values (either 100 or 150%) were used in combination with one of two crop coefficients (K_c; either fixed at 0.75 or 0.2 to 0.8 based upon increasing canopy volume) to calculate the amount of irrigation water required. Five irrigation treatments were: un irrigated control; (100ET) X K_c =0.75; 150ET X K_c =0.75; 100ET X K_c =0.2-0.8; 150ET X K_c =0.2-0.8. Transpiration, water potential (ψ), and soil moisture data were collected each growing seasons. Yield component data was collected and berries from each treatment were analyzed for soluble solids (Brix), pH, titratable acidity (TA), anthocyanins, methyl anthranilate (MA), and total volatile esters (TVE). Irrigation showed a substantial positive effect on transpiration rate and soil moisture; the control treatment showed consistently lower transpiration and soil moisture over the 3 seasons. Transpiration appeared accurately reflect Sovereign Coronation grapevines water status. Soil moisture also accurately reflected level of irrigation. Moreover, irrigation showed impact of leaf ψ, which was more negative throughout the 3 seasons for vines that were not irrigated. Irrigation had a substantial positive effect on yield (kg/vine) and its various components (clusters/vine, cluster weight, and berries/cluster) in 2003 and 2005. Berry weights were higher under the irrigated treatments at both sites. Berry weight consistently appeared to be the main factor leading to these increased yields, as inconsistent responses were noted for some yield variables. Soluble solids was highest

under the ET150 and ET100 treatments both with Kc at 0.75. Both pH and TA were highest under control treatments in 2003 and 2004, but highest under irrigated treatments in 2005. Anthocyanins and phenols were highest under the control treatments in 2003 and 2004, but highest under irrigated treatments in 2005. MA and TVE were highest under the ET150 treatments. Vine and soil water status measurements (soil moisture, leaf ψ, and transpiration) confirmed that irrigation was required for the summers of 2003 and 2005 due to dry weather in those years. They also partially supported the hypothesis that the Penman-Monteith equation is useful for calculating vineyard water needs. Both ET treatments gave clear evidence that irrigation could be effective in reducing water stress and for improving vine performance, yield and fruit composition. Use of properly scheduled irrigation was beneficial for Sovereign Coronation table grapes in the Niagara region. Findings herein should give growers some strong guidelines on when, how and how much to irrigate their vineyards.

Acknowledgments

It has been of a great pleasure to carry out my Masters degree (MSc) in the Department of Biological Sciences, Brock University. This work would not have been possible without the support from many people whom I want to thank. The first words of my endless gratefulness are for my supervisor Dr. Andrew Reynolds who believed, encouraged, and inspired me as well as for his endless support, friendship during all these years we spent together. I thank the Libyan Government represented by the Higher Education Section for the Master's scholarship at Brock University. I would also like to thank the University of 7 April, Azawia, Libya; and to acknowledge the administrative, technical staff, teachers and researchers of the Department of Biological Sciences, Brock University. Special thanks go to Dave Lambert and Larry Hipple for letting us use their vineyards and equipment. Both growers were extremely helpful throughout the seasons. Thanks also go for my graduate committee for having patience and providing valuable constructive criticism throughout this process.

Many thanks go to all my colleagues, students and friends at Brock University, who have been friendly and helpful during these years and for creating a nice atmosphere at work. Thanks also go to Brother Mohamed Elghali for helping me out with all computer matters and programs, and also for his endless encouragement and support. My deepest and unlimited gratitude, love and respect go to my parents, brothers and sisters for the wonderful moral support, love, and everlasting encouragement throughout the different phases of my academic journey. Last but certainly not least, there are no words enough to express my deep love, respect and gratitude to my husband Abdalla Eshtiwi for his love, support, encouragement, and persistence throughout these years. Thanks once more for your invaluable support and endless encouragement all over those fantastic years.

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Introduction

Niagara Peninsula vineyards have typically not been irrigated because of a lack of a perceived benefit for the cost required. The majority of vineyard irrigation used in the world today takes place in areas that experience low rainfall during the growing season and do not have enough water in their soil profile to supply vine growth (Williams 2002). Areas such as California, Australia and Chile use irrigation to supply the necessary water requirements for their vines, and produce very high quality table grapes that under natural drought conditions would not be possible. Several years of drought in the Niagara region has resulted in water stress. Related problems such as those found elsewhere in the world: low yields (Matthews and Anderson 1988, McCarthy 2001), poor fruit composition (Lowrey 2004), decreased vine photosynthesis and transpiration (Chone et al. 2001, Fuller 1997, Gomez-del-Campo et al. 2002, Rodriguez et al. 1993), and poor shoot growth (Reynolds and Naylor 1994, Wolf 1988). These years of drought in the Niagara Regions led many growers to examine the feasibility of irrigation for grapes. Numerous studies indicate that irrigation is a vehicle for overcoming water stress-induced problems (Freeman and Kliewer 1983, Gomez-del-Campo et al. 2002, Williams and Matthews 1990).

The table grape cultivar Sovereign Coronation (Denby 1977) has become widely planted in the Niagara Peninsula. The acreage of Sovereign Coronation has increased substantially in the last few years in Ontario (GGO 2005) and British Columbia (BCMAF 2005). The Fresh Grape and Tender Fruit Marketing Board in Ontario is concerned about determining and achieving optimal maturity for Sovereign Coronation, and irrigation may be an effective way of enhancing fruit maturity, particularly in dry seasons.

Growers of Sovereign Coronation have experienced problems with low sugar, high acid, and low color intensity as the result of drought. Its large berries and extremely large leaves all

underscore its high water requirement. Drought has caused many table grape growers to examine the feasibility of irrigation. There is a great need to do research on irrigation on table grapes, and to gain a better understanding of the impact irrigation has on table grape quality. The greatest concern is the knowledge of when to begin irrigation, how much water to apply, and when to cease irrigation. Irrigation must be applied with precision to replace lost water. Meteorological equations such as the modified Penman-Monteith (1990) are used to accurately schedule irrigation needs by precisely calculating reference evapotranspiration (ET_0) from relative humidity, wind speed, solar radiation, and temperature values that can be downloaded from databases such as the Ontario Weather Network. ET values can then be used with a crop coefficient (Kc; normally based upon canopy volume) to calculate the volume of irrigation water required.

Trials upon which this thesis was based were designed to evaluate how irrigation in a cool, humid climate affects Sovereign Coronation. The trials were initiated in May 2003 in Sovereign Coronation blocks at Lambert Farms, Niagara-on-the-Lake, ON and Hipple Farms, Beamsville, ON. Five irrigation treatments were imposed: non-irrigated control; 100% ET x K_c=0.75; 150% ET x K_c =0.75; 100% ET x K_c =0.5-0.8; 150% ET x K_c =0.2-0.8. Transpiration, leaf water potential, and soil moisture data were collected in June to August 2003 to 2005. Yield components were measured and berries from each treatment were analyzed for soluble solids pH, titratable acidity, anthocyanins, total phenols, methyl anthranilate, and total volatile esters.

A major element of the project consisted of devising a method that properly schedule weekly irrigations in terms of amount of water needed. The Penman-Monteith formula for calculating ET was used in the 3 years of the study as a basis for irrigation scheduling. Vine performance and berry composition were determined to assess their response to irrigation.

Objectives

The general objectives of this study were to assess the effectiveness of using the Penman-Monteith equation for calculating required water volumes, and to validate these calculations based on soil and vine water status measurements. A secondary objective was to examine the efficacy of four irrigation treatments in terms of vine performance and berry composition. The specific objectives of this project were to test combinations of two %ET values and two crop coefficients at two sites in the Niagara Peninsula and compare them to a standard non-irrigated control.

Hypotheses

I hypothesized that: H1: Supplemental irrigation of Sovereign Coronation table grapes using the Penman-Monteith scheduling would enhance vine performance, berry composition, and yield through alleviation of water stress, and; H2: That water budgets calculated from this equation would be validated by measurements of transpiration, water potential, and soil moisture

Literature Review

2.1. Water requirements during vine development.

Vineyard water use depends on the climatic conditions, type of soil, and the size and stage of development of the crop canopy (Williams and Matthews 1990). Given adequate water, vine transpiration is the same for all soil types, but the amount of water that is stored in the soil profile and available for plant uptake is drastically different. This available water is the difference between field capacity and the permanent wilting point (Brady and Weill 1999). The percentage of available water is typically highest in clay soils and lowest in sands (Brady and Weill 1999). Therefore, the soil type and depth of the root zone determine the total available water content in a given vineyard (Peacock and Goldhamer 1998). Field capacity is defined as the point at which a vineyard loses no more water through gravitational drainage (Wolf 1988). Water lost either via direct evaporation or transpiration through stomata within the leaves is called evapotranspiration (ET).

Water uptake by grapevines begins at bud break in late April and early May. Water use gradually increases as the canopy develops and temperatures climb. Typically, the canopy is fully developed by mid-June, and peak water use occurs in June through August in temperate regions of the Northern Hemisphere.

The effect of irrigation on vine growth and fruit development is best discussed by dividing the season into four stages. The *First Stage* covers the period from bud break to bloom (May). The water requirement during this stage is low. This time of year usually has sufficient precipitation and therefore budburst is dependent upon temperature; but water stress during this period has the potential to lead to irregular budburst, short shoots and fewer flowers (McCarthy 2001, Mullins et al. 1992).

The *Second Stage* which covers the period from bloom to the point when fruit begins to soften and show color (veraison), takes place from mid-June to late July for most cultivars in the Northern Hemisphere. Grapevines use large amounts of water during this stage. Proper water management is critical during this stage. Cell division is rapid in the fruit and water stress can reduce berry size and yield (McCarthy 2001, Mullins et al. 1992). At the bloom stage when shoot growth is rapid, water stress can reduce yields and pruning weights due to a decrease in vegetative growth (Christensen 1975, Ludvigsen 1987, Reynolds and Naylor 1994, Schultz and Matthews 1988).

The *Third Stage*, the ripening phase, covers the point from veraison to harvest. It begins at the end of July to mid-August, but harvest varies from late August to November depending on cultivar. During this stage, table grape cultivars should be irrigated sufficiently to avoid water stress and to maximize berry size. Water stress at or following veraison can reduce berry size, berry weight and ultimately yield. Excessive irrigation during this stage can delay fruit maturity (Christensen 1975, Chitteraichelvan et al. 1987, Ludvigsen 1987, Reynolds and Naylor 1994).

The *Fourth Stage* is the post harvest period that concludes with dormancy in late November. During this stage, water is required in amounts to maintain the canopy and to prepare it for the winter. These reserves are made up of carbohydrates produced by photosynthesizing leaves and nitrogen taken up by roots, all of which will contribute to the success of the vine the following season (Ludvigsen 1987). Water stress at this period can hinder reserve accumulation, restrict root growth, and promote early leaf abscission (McCarthy 2001). In northern climates, where winters are harsh and cold, wood reserves play a key role in preventing winter damage due to cold temperatures (Wolf 1988).

Figure 1: Stages in grapevine shoot development (Eichhorn and Lorenz 1977).

2.2. Irrigation.

Irrigation is critical for good growth and production in arid regions and is essential to meet a balance between water input and water loss. The amount of irrigation water needed is normally equal to vineyard ET (evapotranspiration) minus annual precipitation (Williams 2001, Williams and Matthews 1990). Irrigation management in the table grape industry has become an important issue, as many regions of the world that are significant table grape producers have hot, arid climates. Production in Australia, California, Spain and Chile is limited by water quantity and quality (Hardie and Considine 1976, Smart 1974, Smart and Coombe 1983). Inadequate irrigation induces water stress and can lead to problems such as black leaf disorder (Ludvigsen 1987). Excess irrigation can delay ripening, often due to increase vegetative growth which can

cause dense shady canopies (Reynolds and Naylor 1994, Smart 1983, 1985). This uncontrolled canopy development may lead to poor juice quality because of low sugar and high pH and K content, greater disease incidence (Fuller 1997, Smart 1985, 1997). K relocation from vegetative structures of the vine to the fruit during ripening negatively affects juice quality (Smart et al., 1985). They hypothesized that K cations are exchanged for hydrogen ions in the berries, thus increasing juice pH and lowering its potential quality (Lowrey 2004).

Irrigation methods vary in terms of application technique, timing, and volume discharged. Water applied by surface means can produce runoff that exceeds standards for water quality. Regulated deficit irrigation (applying less than replacement ET) may improve fruit quality by controlling the growth of the canopy, reducing the size of the berries, and exposing the fruit to sunlight (Ludvigsen 1987, Reynolds and Naylor 1994, Smart 1997, Williams 2002). A well-known method used by growers to save water and reduce exorbitant water costs is use of drip irrigation. Today, drip irrigation is widely used, and the technology has evolved in all areas from irrigation scheduling and engineering to managing soil and water chemistry. The advantages with using drip over other methods such as overhead or flood irrigation is its ability to restrict the water to each vine, which leads to less wasted water. Additional advantages include less soil erosion and lower incidence of fungal disease by preventing foliar wetting (Coombe and Dry 1998).

Water stress in grapevines may cause many problems such as reducing photosynthesis due to reduced stomatal conductance (Carbonneau et al. 1983, During 1990, Freeman et al. 1982, Schultz 1996). Water stress reduces the amount of dry matter produced by the vine and consequently reduces leaf area formation (Fanizza et al. 1990, Kliewer et al. 1983, Miller et al. 1996). Shoot growth and early berry development are especially sensitive to water stress (Fanizza and Castignano 1993, Smart 1974), making the early to mid-season a critical time in terms of irrigation scheduling.

The purposes of using vineyard irrigation are to provide vines with sufficient amounts of water that can compensate for lack of rainfall or water losses via the water cycle. Advantages of using irrigation include overcoming drought problems, improving vine vigor (shoot length), increasing yields. Moreover, irrigation increasing photosynthetic activity, alleviating water stress during critical periods of vine growth and fruit development, and preventing significant winter injury (Fanizza and Castrignano 1993, Freeman and Kliewer 1983, Ginestar et al. 1998, Hardie and Considine 1976, Herper et al. 1985, Ligetvari 1986, Ludvigsen 1987, Rodrigues et al. 1993, Smart 1983, 1985, Williams 2001, Wolf 1988). Irrigation also has some disadvantages; irrigation may decrease fruit quality by increasing shading, increase the chance for disease, decrease pH, and lower sugar accumulation (Fuller 1997, Smart 1985).

2.3. Scheduling irrigation using ET, such as Penman-Monteith equation.

One means of determining how much water should be applied and when irrigation should be supplied is using a soil water balance, or soil water budget. This involves keeping an account of water input into the soil (rainfall and irrigation) and water output (ET and drainage) on a daily basis. Although rainfall and irrigation amounts are easily measured on the farm, estimating the ET and drainage are complex procedures. As evapotranspiration is the greatest way in which plants lose water, most water balance irrigation scheduling methods are based on a daily estimate of the reference evapotranspiration (ET_0 mm/day) direct evaporation or transpiration through stomata in the leaves, which is then modified according to the crop being grown. Many equations have been developed to estimate evaporative losses in both hydrological systems and ecological systems. There are some meteorological equations used to estimate ET such as the original Penman equation (1948), the Kohler-Nordensen-Fox equation (1955), the Blaney-Criddle equation (1956), the Christiansen equation (1968), the Priestly-Taylor equation (1972), and the Linacre equation (1977). These were compared in terms of their accuracy by Irmak and Haman (2003).

The Penman (1948) equation (Figure 2) is relevant to this study because it was later modified into the Penman-Monteith equation, which was used extensively in this experiment to calculate evaporative loss (E_{pan}). The Penman-Monteith equation (Figure 3), developed in 1990 by the United Nations Food and Agriculture Organization (FAO), calculates a reference evapotranspiration value (ET_0 in mm/day), which can be used further to determine water requirements and thus irrigation scheduling. Weather data such as net radiation, air temperature, and wind speed; saturation vapor pressure, actual vapor pressure, saturation vapor pressure deficit, and slope of the vapor pressure curve (calculated using relative humidity data); and, the psychrometric constant (determined using elevation and atmospheric pressure) are all used in the equation to calculate ET.

$$E_{pan} = \frac{6.43\,(1+0.53\mu_2)(e_s-e_a)}{\lambda}$$

Variables

μ_2 wind speed at 2m height (m/s)

$(e_s - e_a)$ vapour pressure deficit (kPa)

λ latent heat of vaporization of water = 2.45MJ/kg

Figure 2: The Penman (1948) equation for estimating evaporation.

$$ET_o \text{ (mm/day)} = \frac{0.408\Delta(R_n - G) + \frac{900}{(T_{ave}+273)} \mu_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)}$$

Variables:

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
e_s - e_a saturation vapour pressure deficit [kPa],
Δ slope vapour pressure curve [kPa °C^{-1}],
γ psychrometric constant [kPa °C^{-1}].

Figure 3: FAO Penman-Monteith equation.

After ET_0 is determined, it can be multiplied by a crop coefficient factor (K) to determine the ET_C or crop evapotranspiration. Crop coefficients are based on the amount of ground covered by that crop in comparison to the reference crop. Vineyard crop coefficients range from 0.2 to 0.8 based on canopy volume. From this point, the amount of water required by that crop can be determined using the following equation (Figure 4), that was developed by British Columbia Ministry of Agriculture and Fisheries (Van der Gulik and Eng 1987).

$$\text{Liters/vine/day} = 0.623 \times 3.785 \times ET_0 \times S \times A \times K$$

where, $0.623 = \dfrac{\text{27 152 US gallons/acre-inch}}{\text{43 560 feet}^2\text{/acre}}$

3.785 = conversion from US gallons to liters

ET_0 = reference evapotranspiration

S = soil water storage factor

A = plant area

K = crop coefficient factor

Figure 4: Equation for determining water needs based on crop coefficients, plant area, and soil type.

2.4. Effects of irrigation on vine performance.

The most important objectives of applying irrigation water to grapevines are to produce high yields and high quality fruit. The amount of water applied may vary from year to year, depending on the density of the vine canopy, the soil resources, cultivar, and climatic conditions of both the previous and current seasons (Austin and Bondarl 1988, Cifre et al. 2005, Morris 1989). Grapevines have a tendency to produce dense, shaded canopies, which can reduce fruit exposure, air movement, and fruit quality (Smart et al. 1985), and it is therefore essential that irrigation volumes be tailored to control this tendency. Vineyards can be very different in terms of soil water availability, vigor, and trellis design. All of these aspects exclusive of irrigation can significantly affect vine performance, production level, and fruit quality (Austin and Bondarl 1988, Cifre et al. 2005, Morris, 1989). Some grapevine cultivars do not generally show direct signs of water stress, but will show symptoms of constant stress by increasing effects on shoot or fruit development (Williams et al. 1994). Water stress has an extensive range of effects on grapevine growth, development and physiology depending on the phenological stage at which the water stress occurs (Austin and Bondarl. 1988, Cifre et al. 2005). When water stress occurs for the duration of bud break and near the beginning of shoot development, it may result in rough

bud break, small shoot growth, poor flower-cluster development and reduced pistil and pollen viability and subsequent berry set (Hardie and Considine 1976). A recommended mahod to avoid early stress is to keep soil moisture levels around the stable wilting point for that particular soil (Ludvigsen 1987). Following berry set, severe water stress causes flower abortion and cluster abscission, due to hormone changes which lead to reduced canopy development and, consequently, deficient leaf area to sufficiently maintain fruit development and maturation (During 1986). After the fruit set stage, water stress limits berry cell division and growth, resulting in smaller fruit and lower yield. Following early berry development is the lag phase, which is less at risk to water stress as the previous phases, but water stress at this phase could reduce shoot, canopy development, and limit the photosynthetic capability of the vine. Fruit development and quality can be limited leading to reduced yield and fruit soluble-solids accumulation (Cifre et al. 2005).

Severe water stress in vines can be most damaging during late spring and early summer, when shoots grow rapidly and cell division occurs in the berries. Poor berry set and smaller berries result from severe stress in late spring and early summer (Austin and Bondarl 1988, Morris 1989). A second serious period is during late summer, when cell expansion takes place in the berry. Severe water stress during late summer when ripening stage takes place can reduce berry size and may delay or, under very severe conditions, prevents fruit maturation (During 1986, Freeman et al. 1980, Ginestar et al. 1998). Drought conditions require using water with greatest efficiency. Growers should regularly monitor soil moisture and apply water only when needed or at calculated times during the delivery period (Lowrey 2004).

Vitis labruscana grapevines are grown in the cool, humid climate of North America. The grapes are used mostly for fresh juice. *V. labruscana,* cultivars have somewhat smaller root systems than other grape species (Lakso et al. 2003). Under all but the extreme drought situations, vine survival is probable, even though crop quality and yield may be low. *V.*

labruscana, cultivars are particularly drought sensitive, and water stress can slow fruit maturity and reduce nutrient uptake (Grant 2002). In newly planted vineyards, water management is important for providing sufficient irrigation for vine establishment (Lakso 1993). Fruit quality in *V. labruscana* mostly depends upon sugar level, titratable acidity, and flavor constituents including methyl anthranilate and other volatile esters as well as tannins and color substances (Morris 1989, Robinson et al. 1949). The composition of juice from any *V. labruscana* cultivar can never be assumed because composition changes frequently during ripening, and varies from year to year, and from area to area depending upon soil type and climatic conditions (De Golier 1978, Morris 1989).

High quality *vitis vinifera* are a high value product and an important export crop for many countries. Fruit appearance is important to the consumer. Table grape growers are constantly facing challenges in the marketplace and need to be skilful in their production practices. Optimizing vineyard management practices such irrigation to assure optimum fruit composition and sensory quality has been addressed in several studies. Numerous studies indicate that irrigation is a vehicle for overcoming water stress-induced problems in table grapes (Carreno et al. 1997, Gomez-del-Campo et al. 2002, Williams and Matthews 1990).

2.4.1. Effects of irrigation on yield.

Yields of most crops are directly related to the volume of consumed water; therefore full potential water use is desirable. Chardonnay showed about 20 to 25% yield increases in irrigated vines (Balo et al. 2002). Vines under water stress have been revealed to produce lower berry weights than do irrigated vines (Cline et al. 1985, Goodwin and Jerie 1989, Reynolds and Naylor 1994, Williams and Matthews 1990, Williams et al. 1987). Several studies have shown that increased irrigation applications result in higher berry weights (Christensen 1975, Smart 1985, Williams and Matthews 1990). More water available to vines during the ripening process is taken in by the berries, resulting in an increase in size and weight of the berries.

Most important Concord-producing regions in the northeastern United States produce adequate grape yields without irrigation; few studies on the effects of supplemental irrigation on juice quality have been conducted. Nevertheless, supplemental irrigation can increase yields of many crops and is suggested for regions with dry environment and shallow soils). Supplemental irrigation of Concord and Niagara juice grapes according to Penman-Monteith scheduling, will improve vine performance and berry composition by elevating of water stress. Increased yields should result. A study of Concord and Niagara suggested that irrigation of labrusca cultivars leads to improved berry set, larger berry size, increased vigor and a consequential slight increase in yield (Reynolds et al. 2005).

2.4.2. Effects of irrigation on soluble solids.

Water stress reduces the amount of dry matter and leaf area produced by the vine (Fanizza et al. 1990, Kliewer et al. 1983, Miller et al. 1996). Non-irrigated vines often become excessively water stressed, resulting in low sugar production, low yield, and poor juice (Freeman et al. 1980, Ginestar et al. 1998). Irrigation leads to more shoots per vine, longer shoots, larger leaves and lateral growth (Ludvigsen 1987). Consequently, increased leaf area may lead to greater rates of photosynthesis and nutrient transport (Balo et al 2002). Photosynthesis produces the sugar accumulates in berries, while water loss due to transpiration increases the overall sugar concentration in soluble solids (Dreier et al. 2000). On the other hand, irrigation can have little effect on soluble solids concentration (Brix) (Ginestar et al. 1998, Goodwin and Jerie 1989, Ligetvari 1986, Ludvigsen, 1987, Williams and Grimes 1987), and in some cases, increasing water stress has increased juice soluble solids (Reynolds and Naylor 1994, Rodrigues et al. 1993). Varying irrigation scheduling also has been shown to affect Brix. Water applied at the end of veraison increased yield slightly, and kept soluble solids constant (Rühl and Alleweldt 1985). Moreover; in some grape cultivars such as Concord, irrigated vines produce fruit with higher soluble solids, despite increased yield (Cline et al. 1985). Fruit composition may also be

compromised by water stress at veraison as ripening is accelerated, resulting in both retarded sugar accumulation and poor flavor development (McCarthy, 2001).

In *Vitis labruscana*, the quality of grape juice largely depends upon sugar level (Cline et al. 1985, Morris 1989). Conditions that occur during growth and maturation determine the quality of the juice (Morris 1980, 1989). The Concord grape juice industry has determined that the best index for optimum maturity is soluble solids (Brix) and that Ideal flavor, acid and color occur in Concord grapes when the soluble solids level is between 16 and 17 (Morris and Striegler 1996, Morris 1989). Irrigation delays fruit maturity as indicated by lower soluble solids, higher titratable acidity, and lower juice color intensity at harvest compared to non-irrigated vines. Delaying harvest will help to overcome this problem and may justify the additional yields in irrigated vineyards (Morris and Cawthon 1982, Morris et al. 1989, Shaulis et al. 1966, Spayd and Morris 1978). A study on Concord and Niagara suggested that irrigation of *V. labruscana* cultivars leads to reduced soluble solids, although all soluble solids levels in the study were beyond the minimum levels accepted by local processors (Reynolds et al. 2005).

2.4.3. Effects of irrigation on titratable acidity and pH.

Two other important variables in determining fruit quality are titratable acidity (TA), which is a measure of the undissociated acids and free hydrogen ion concentration in solution, and pH, which measures only free hydrogen ion concentration in solution (Margalit 1996, 1997). The primary acids of grape are tartaric, malic and citric. Supplemental irrigation has been shown to increase juice TA (Cline et al. 1985, Ligetvari 1986). Other studies showed no effect of irrigation on TA and pH (Chittiraichelvan et al. 1987, Ginestar et al. 1998, Goodwin and Jerie 1989). Juice acidity is typically not affected by irrigation by the final harvest (Morris 1980). However, the negative impacts of water stress are not eliminated after the fruit is harvested. For example, post-harvest, the vine accumulates photosynthesis-derived carbohydrates in the wood reserves in preparation for winter season (Lowrey 2004, Ludvigsen 1987). Non-irrigated soils clearly

provide less than ideal conditions for reserve accumulation at this time, because they limit root growth and promote early leaf abscission (McCarthy 2001). A deep understanding of the mechanisms that control plant carbon adaptation and partitioning under different water regimes is of great interest since these mechanisms play an important role in the regulation of the fragile balance between grape yield and quality. Eventually, this will lead to the description of physiologically based criteria for irrigation scheduling (Cifre et al. 2005). In northern climates, where winters are harsh and cold, wood reserves play a key role in preventing winter damage due to cold temperatures (Lowrey 2004, Wolf 1988).

In *V. labruscana*, the quality of grape juice depends somewhat upon titratable acidity (Cline et al. 1985, Morris 1989). A study of Concord and Niagara however suggested that irrigation had no major effects on titratable acidity or pH among various irrigation and fertigation treatments (Reynolds et al. 2005).

2.5. Effect of irrigation on secondary metabolites, including: phenols, anthocyanins, monoterpenes, methyl anthranilate and volatile esters.

The specific composition of fruit from any grape species can never be accurately predicted, since composition varies from year to year and changes continually during the maturation and ripening processes in the field (Esteban et al. 2001). The composition of a given cultivar will vary from place to place depending upon the soil, and the climatic conditions (Austin and Bondarl 1988, Cifre et al. 2005, Morris, 1989). Color is a particularly important quality attribute in table grapes. Color is a quality factor of primary importance in foods, as visual appreciation is the first of the senses to be used, acting as a decisive characteristic in food choice.

The production of grapes with desirable concentrations of flavor and aroma compounds at harvest is the result of the meeting of two broad influences (Hardie et al. 1996). The first is the reproductive process through seed progress, which determines potential berry size. Because the skin contains high concentrations of these compounds, the berry surface to volume ratio is

important in determining the amount of these compounds. The second influence on the production of flavor and aroma compounds comes from environmental factors and viticultural management. Viticultural conditions and practices that influence secondary metabolites include macro and mesoclimate (Jackson and Lombard 1993), regulation of water supply (Hardie and Martin 1990), regulation of leaf area to crop ratio and canopy management practices that influence the light exposure of leaves and fruit (Iland et al. 1993).

2.5.1. Effect of irrigation on anthocyanins and phenolics.

Grape cultivars can be classified according to the color of their skins (Carreno 1997). The pigments responsible for the attractive red, blue, purple, and black color are anthocyanins, a class of water-soluble flavonoid pigments located in the skin. In *Vitis vinifera*, the anthocyanins stand out among the compounds that have frequently been used as chemical markers in chemotaxonomy, and it is well known that their distribution in grape is complex and varies according to the cultivar (Pomar et. al. 2005). Inside the cells, they are located in the vacuoles, in a free, non-complex form (Ortega et al. 2005). In addition to color, they contribute to the organoleptic and chemical properties of grapes, because of their interaction with others phenolic compounds as well as with proteins and polysaccharides (Carreno et al. 1997, Pomar et. al. 2005). The composition of anthocyanins is primarily determined by genetic factors, however, the content of anthocyanins in grapes changes during their maturation, and seasonal conditions and the physical and chemical characteristics of the soil influence the distribution of anthocyanins in grapes (Carreno et al. 1997, Esteban et. al. 2001). On the other hand, most of references coincide with the fact that the non-genetic factors such as several environmental conditions or viticultural practices have a greater effect on the concentration of anthocyanins rather than on their relative distribution in the skin of the fruit (Carreno et al. 1997, Esteban et. al. 2001, Pomar et al. 2005).

Viticultural practices such as irrigation are designed to control vine vigor, increase yield, improve fruit ripening, and may improve color development (Smart 1985, Williams and Matthews 1990). Irrigation during the period after flowering resulted in the greatest production in berry weight, especially in years with high temperature summation (Ginestar et.al. 1998). In general, water deficits increase fruit components like anthocyanins, and phenolics due to reductions in vegetative growth and berry weight (Ginestar et al. 1998, Hardie et al. 1976, Matthews and Anderson 1988, Reynolds and Naylor 1994).). Irrigation deficits particularly increase phenolic compounds, which add to astringency and wine aging characteristics (Bravdo et al. 1985). On the contrary, water deficits after veraison had only a minor effect on berry weight at maturity and berries were insensitive to water deficits during the month before harvest (McCarthy 1999). Irrigation may increase berry weight and size, and this decreased skin-to-volume ratio may reduce the overall concentration of color and flavor-producing compounds (Dreier et al. 2000, Ginestar et al. 1998, Williams and Grimes 1987). Excess irrigation may lead to fruit shading, which will decrease the skin color of some cultivars (Archer and Strauss 1989). Shaded clusters caused a reduction in the phenol and anthocyanin concentrations, while shading of the leaves caused a delay in berry growth and sugar accumulation (Morrison and Noble 1990). Bergqvist et al. (2001) showed that anthocyanin concentration in grapes increased linearly as sunlight exposure increased. Color improves with greater light exposure, but due to the inherent dangers of heat stress, vineyards should be judged on an individual basis, with the canopy management system complementing the specific climatic conditions. In terms of specific constituents, cluster sun exposure appears to be the key factor determining quercetin-3-glucoside concentrations in grapes (Haselgrove et.al. 2000). The magnitude of this response to sun exposure seemed large enough to affect fruit composition and quality. Anthocyanin metabolism responds to changes in both light and temperature conditions and the optimum temperature for the enzymes involved in the anthocyanin biosynthetic pathway is between 17 and 26C (Pirie and

Mullins 1977). It is clear from the examples mentioned that sun exposure has a significant effect on the phenolic composition of grapes. Controlling the leaf area/crop weight will improve berry coloration and accelerate ripening (Kliewer and Dokoozlian 2000). Irrigation may affect these factors.

2.5.2. Effect of irrigation on terpene compounds.

Some data supports the idea that reducing irrigation could lead to an increase in the concentration of flavor compounds (terpenes) in the fruit (McCarthy 1986, McCarthy and Coombe 1985, McCarthy et al. 1987). Others have shown that early irrigation deficits were detrimental to flavor development (Reynolds and Wardle 1997, Reynolds et al. 2006). In wine grape cultivars, smaller berry size (larger surface-to-volume ratio) is preferred. This increased skin-to-volume ratio in turn increases the overall concentration of odor-active compounds (Dreier et al. 2000, Ginestar et al. 1998, Williams and Grimes 1987).

2.5.3. Effect of irrigation on esters.

In *V. labruscana* grapes, methyl anthranilate is an important odor active compound, and was one of the first compounds to be associated with the aroma of that particular grape species (Fuleki 1982, Morris 1989). The biosynthesis of methyl anthranilate, the volatile compound responsible for the distinctive foxy aroma and flavor of some cultivar of grapes involves an alcohol acyltransferase that catalyzes the formation of methyl anthranilate from anthraniloyl-coenzyme A (CoA) and methanol (Wang and DeLuca 2005). Anthranilic acid is an intermediate product of the shikimate pathway that is produced on the way to tryptophan biosynthesis. Some have speculated that it accumulates in grapes in its methylated form during the latter period of fruit maturation as a tryptophan breakdown product (Reynolds et al. 1982).

The organoleptic quality of *V. labruscana*-based grape juice largely depends upon flavor components such as methyl anthranilate and other volatiles (Cline et al. 1985, Morris 1989).

Flavor and aroma develop during the ripening process. Supplemental irrigation of Concord and Niagara grapes may improve vine performance and berry composition by reducing water stress. Minor reductions in flavor compounds such as methyl anthranilate and volatile esters, esters may result from reduced water and nitrogen stress (Hoenicke et al. 2001). A study on Concord and Niagara, however, suggested that methyl anthranilate concentrations were very sensitive to drought; therefore, under severe water stress, berries from non-irrigated control treatments had lowest concentrations of this compound (Reynolds et al. 2005). A series of features including soil type, method of irrigation, severity of water stress, and amount of water added all possibly played contributing roles.

Esters such as methyl anthranilate are formed by esterification that combines carboxylic acid and an alcohol. In grape berries, oxidation in the fats and waxes on the skins produces carbon polymers of various lengths (6, 8, and 12 carbons) (Tressl and Drawert 1973). These form the basis for acid and alcohol formation. The effect of irrigation on volatile ester compounds has not been well studied. However, (Reynolds et al. 2005) found that methyl anthranilate values for Niagara and Concord berries were highest from full season irrigation treatments for both years of the study. They also found that non-irrigated control and irrigated vines produced volatile ester values for Niagara that were quite similar in both years (Lowrey 2004, Reynolds et al. 2005).

2.6. Irrigation and water relations in table grapes. Experience from warm climate regions.

The table grape cultivar Sovereign Coronation (Denby 1977) has become widely planted in the Niagara Peninsula. The acreage of Sovereign Coronation has increased considerably in the last few years in Ontario (GGO 2005) and British Columbia (BCMAF 2005). The Fresh Grape and Tender Marketing Board's main concern is based on the quality of the product, both in terms of flavor and texture, and how high quality can be achieved. All growers of Sovereign Coronation have found problems with low sugar, high acid, and intensity of color.

For grapevines, irrigation remains the most probable way to reduce drought impacts on yield. Consequently, efficient water use through regulated deficit irrigation programs would be one of the most desirable tools to improve water-use efficiency and crop productivity in semi-arid areas (Cifre et al. 2005). The recent overview of vine irrigation in countries with dry summers suggests the existence of some controversy, due to the not fully understood relationships between grapevine photosynthesis and fruit yield and quality. Irrigation significantly increases photosynthesis, and 1.5 to 4- fold, depending on irrigation timing, amount of water applied, cultivar, environmental conditions and other cultural practices (Bravdo et al. 1985, Cifre et al. 2005, Escalona et al. 2003, Hepner et al. 1985, Matthews et al. 1987, Schultz 1996, Williams 1996), increases grape yield. Up to a specific amount of added water, no ill effects are observed on grape quality, even when yield is increased (Bravdo et al. 1985, Cifre et al. 2005, Hepner et al. 1985, Medrano et al., 2003). Conversely, larger amounts of water, though further increasing grape yield, have a depressing effect on quality, mostly due to color losses, low Brix, and acidity imbalances (Bravdo et al. 1985, Cacho et al. 1992, Cifre et al. 2005, Esteban et al. 1999, 2000, Hepner et al. 1985, Matthews et al. 1990). Consequently, a deep understanding of the mechanisms that control plant carbon adaptation and partitioning under different water regimes is of great interest in the frame of precision agriculture, since these mechanisms play an important role in the regulation of the fragile balance between grape yield and quality. Eventually, this will lead to the description of physiologically based criteria for irrigation scheduling (Cifre et al. 2005).

Materials and Methods

3.1. Experimental design.

Experiments were conducted at Lambert Vineyards in Niagara-on-the-Lake ON, and at Hipple Vineyards, Beamsville, ON, from May 2003 to October 2005. Vines at Lambert Vineyard were 12 years old at the initiation of the trials. The experimental block consisted of twenty-five rows each containing 129 Sovereign Coronation vines leaving the outside row as a buffer. Experimental design was a randomized complete block with five treatments. Each treatment replicate was an entire vineyard row. Within each row, ten equally spaced vines were chosen as data collection points. Training was four-arm Kniffin, whereby vines were pruned to four, 10-node canes plus four, two-node renewal spurs. Spacing was 1.5 m X 2.5 m (vine X row). Pest and soil management were consistent with local recommendations (OMAF 2003). Soil at the Lambert site was made up of a combination of two phases of the Chinguacousy soil series: loamy red phase and red phase (Kingston and Presant 1989). The wilting point of the Ap horizon was 13.3% moisture, and field capacity was 27.3 % moisture (Kingston and Presant 1989) (Figure 5).

The Hipple Vineyard contained vines that were 8-years old at the initiation of the trials. The experimental block consisted of 15 half-rows, each containing 100 Sovereign Coronation vines. Water supply to each half-row was controlled by its own valve. The trial consisted of three blocks; as at the Lambert site, each block contained five treatments arranged in a randomized complete block. Each treatment replicate consisted of an entire half-row of vines. The outside rows were used as buffers. Within each row, ten equally spaced vines were chosen as data collection points. Vines were spaced at 1.4 m X 2.7 m (vine X row), trained to a four-arm Kniffin system, fertilized with 200 kg per ha of 33-0-0 in spring and 350 kg per ha of 0-0-60 every other year in the fall, with floor management consisting of discing every other row and rye grass planted in July in the remaining rows. Pest management consisted of a standard spray

program (OMAF 2003). Soil at the Hipple site was heavy Morley clay whose moisture retention characteristics are not described; however, a similar soil series (Lincoln) has a wilting point of 25.0 % moisture and a field capacity of 42.3 % moisture (Kingston and Presant 1989).

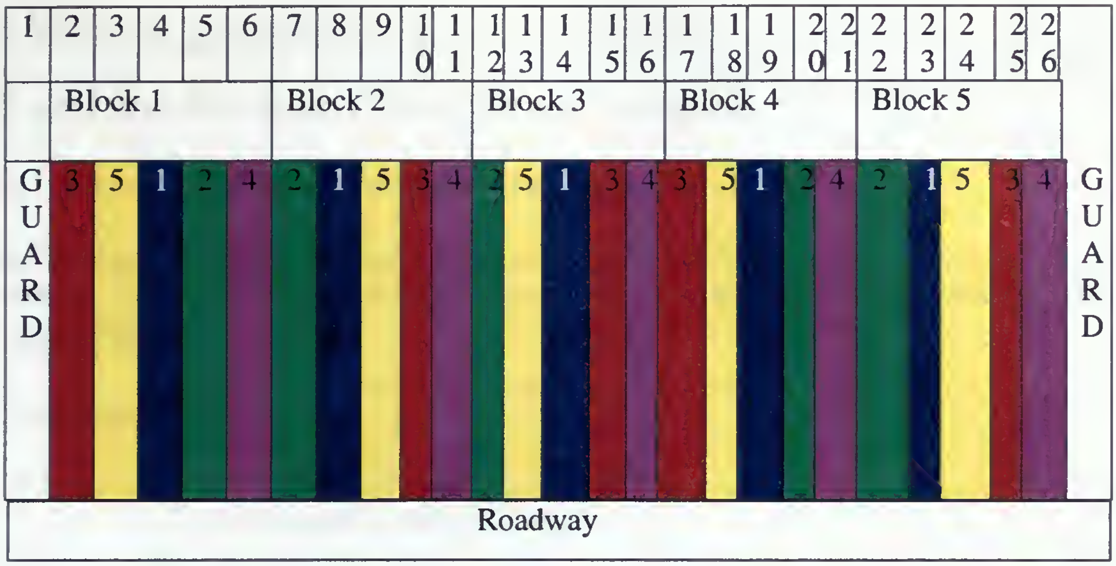

Figure 5: The experimental design and treatment layout for the Lambert site. Numbers at the top of the table are row numbers. Those in each cell are treatment numbers (Table 1). North is at the top of the plot map.

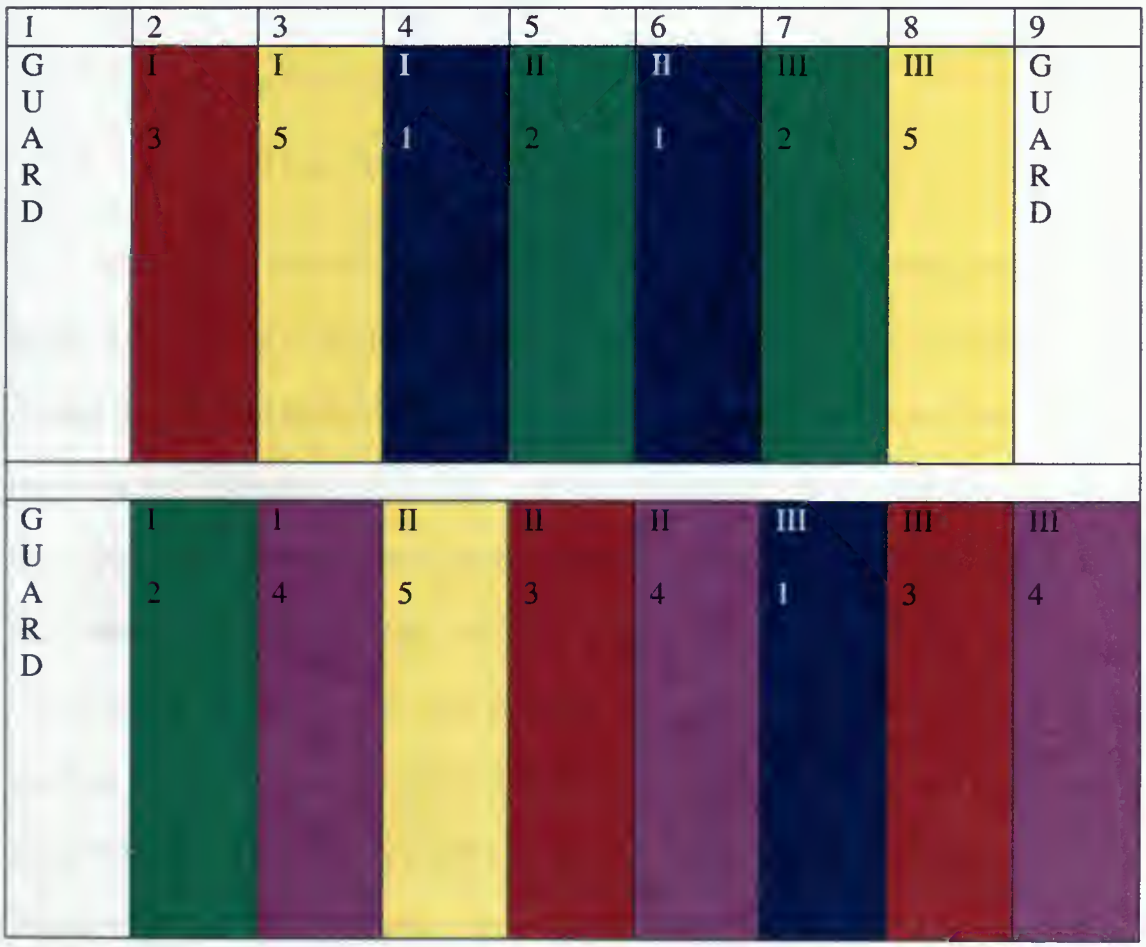

Figure 6: The experimental design and treatment layout for the Hipple site. Numbers at the top of the table are row numbers. These in each cell are treatment numbers (Table 1). I, II, III are blocks. North is at the bottom of the plot map.

The five irrigation treatments on each of the two sites were: non-irrigated control; 100% ET X K_c=0.75; 150% ET X K_c =0.75; 100% ET X K_c =0.2-0.8; 150% ET X K_c =0.2-0.8. (Table1). Within each row, ten vines were chosen for data collection.

Table 1: Description of irrigation treatments applied of Sovereign Coronation grapevines, at Lambert Vineyards in Niagara-on-the-Lake ON, and at Hipple Vineyards, Beamsville, ON. 2003- 2005.

Treatment	Description
1	Non-irrigated control
2	100ET X K_c =0.75
3	100ET X K_c =0.2-0.8
4	150ET X K_c =0.75
5	150ET X K_c =0.2-0.8

The irrigation system consisted of a gasoline-powered pump to bring water to all the rows. RAM (Netafim Corp., CA) drip tubing was placed down the rows close to the base of the vines. A valve that allowed application of water needed to the individual rows at various times through out the season individually controlled each line of irrigation tubing. Emitters were rated at 8L/hour, and the spacing of the drippers was 40 cm. All water was passed through a sand filter.

3.2. Penman-Monteith Equation and ET values; irrigation scheduling.

For determining the vine water requirements for a particular week, weather data from the previous week had to be collected. The FAO Penman-Monteith equation was used to calculate the reference evapotranspiration (ET_0) for the site based on weather variables. The Ontario Weather Network (OWN) supplied daily weather information such as: temperature (maximum, minimum, and average), relative humidity (both maximum and minimum), net radiation, precipitation and wind speed. The ET_0 was then used, along with different crop coefficients (K_c

=0.2-0.8) to calculate the actual amount of water required by the vines, in L/vine/day. The mathematical steps taken to schedule irrigation applications are shown next (Tomek 2003).

Step 1: Receive weather information for "week 1": Net radiation (Rn), maximum and minimum relative humidity (RH_{max} and RH_{min}), maximum, minimum, and average temperatures (T_{max}, T_{min}, T_{ave}), and wind speed μ_2.

Step 2: Calculate the following:

- $e°(T_{max}) = 0.6108 \exp [(17.27)(T_{max})/(T_{max}+273.3)]$
- $e°(T_{min}) = 0.6108 \exp [(17.27)(T_{min})/(T_{min}+273.3)]$
- $e°(T_{ave}) = 0.6108 \exp [(17.27)(T_{ave})/(T_{ave}+273.3)]$
- $e_s = [e°(T_{max}) + e°(T_{min})]/2$
- $e_a = [(e°(T_{min}))(RH_{max})/100) + (e°(T_{max}))(RH_{min}/100)]/2$
- $\Delta = [(4098)(e°(T_{ave})]/(T_{ave}+237.3)^2$
- $P = 101.3(293-(0.0065)z/293]^{5.26}$, where z=300m in elevation for the site
- $\gamma = (0.665 \times 10^{-3})(P)$

Step 3: Calculate ET (mm/day) using the FAO PM equation:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where G=0

Step 4: Convert ET (mm/day) to (inches/day):

ET (in/day) = ETo (~~mm~~/day) x 1/25.4 (inch/~~mm~~)

**Note: This step is performed because the FAO PM equation only generates metric values whereas the next step requires imperial units

Step 5: Refer to the B.C. Trickle Irrigation Manual (Van der Gulik and Eng 1987) and determine the following:

- s = available water storage capacity = 2.4 inches /foot of soil
    - Based on soil type
    - Lambert's farm falls under clay loam category.
    - Hipple's farm under clay category
- d = effective rooting depth for grapes = 4 ft
- a = availability coefficient for grapes = 40%
- S_c = effective soil water storage capacity = (S_c = s x d x a) = 3.84 inches
- S_f = effective soil water storage factor = 0.75
    - Value if based on calculated S_c
    - Thus, if S_c =3.84, then S_f = 0.75 (Van der Gulik and Eng 1987)
- K_c = crop coefficient for grapes = 0.70
- A = plant area = 5ft x 8 ft = 40 ft^2

Step 6: Calculate volume of irrigated volume in US. gallons/vine/day:

G_{irrig}/P/D = 0.623 (gallons / ~~in~~· ~~ft2~~) x ET_0 (~~in~~/day) x S_f x A (~~ft2~~) x K_c

= 0.623 x ET_0 x 0.75 x 40 x 0.70 (gallons/day)

Step 7: Convert US gallons/vine/day to L/vine/day:

L_{irrig}/V/D = G_{irrig}/P/D x 3.78 (L/gallon).

Step 8: Take a 7 day sum of the L/vine/day to calculate L/vine/week

Step 9: Take a weekly total of mm of rain received.

Step 10: Subtract 12 mm from the total amount of rainfall to calculate the millimeters of rain that actually entered the soil and is accessed by the vine.

**Note: This step is taken because 12mm represents the amount of rain that does not percolate into the soil.

Step 11: Convert the actual mm of rain to L/vine.

L_{rain}/vine/week = mm of actual rain/25.4mm x 122,530L/1200vines

**Note: One acre-inch of rain (25.4 mm rain) is equal to 122,530L, and one acre has 1200 vines, therefore 1 acre-inch of rain will provide one vine with 122,530/1200 or 102.1 L/vine.

Step 12: If a positive value is generated in Step 11, then subtract this from the value calculated in Step 7. This will calculate the actual volume of irrigation required per vine for that week. A negative value generated in Step 11 is deemed it negligible:

(L_{actual}/V/W) = [($L_{irrig.}$/V/W of irrigation) – (L_{rain}/vine/week received by vine)]

Step 13: Calculate the hours of irrigation required to output the actual volume for that week. The rate of output for the irrigation pumping system is required for this calculation.

Hours of irrigation = L_{actual}/V/W) ÷ L_{output} / h.

The calculated amount of water required was then applied to the vineyard the following week.

3.3- Vine and soil water status.

The objectives of these experiments were to accurately schedule irrigation using meteorological equations and then validate these calculations with measurements of vine and soil water status. Every week from late June to late August 2003, 2004 and 2005, irrigation treatments were applied when needed, and water status data were collected.

3.3.1- Soil moisture.

Soil moisture data were taken weekly in 2004 and bi- weekly in the 2003 and 2005 growing seasons and were measured one day after irrigating the treated vines. Soil moisture

levels were evaluated via a Theta Probe model ML2X (Delta-T Devices Ltd., Cambridge, UK). Probe readings (m^3 water/ m^3 soil) were taken at each of 10 vines per row. 250 vines at the Lambert farm and 150 vines at the Hipple site were marked and measured between 0900h and 1200h. Measurements were taken in the row ca 20 cm from the base of each vine trunk. Soil moisture was integrated over a 100 mm depth.

3.3.2- Water potential.

Measurements of leaf water potential (ψ) were taken weekly in 2003 and 2004 and bi-weekly in 2005. Water potential was measured using Model 3005 Plant Water Status Console (Soil Moisture Equipment Corp., Santa Barbara, CA), which applied pressure to a severed leaf with an intact petiole. As soon as liquid showed from the cut end of the petiole, the applied pressure corresponding to the magnitude of the tension in the leaf xylem the leaf ψ was noted and recorded (measured in bars; 10 bars = 1 MPa). Leaf ψ measurements were taken from one block (block 2 at the Hipple site and block 4 at the Lambert site) from two vines/row and four mature exposed leaves/vine. Water potential was sampled hourly between 1100h and 1500h.

3.3.3- Transpiration.

The LI-1600 steady-state porometer (Li-Cor Inc., Lincoln, NE) was used to measure transpiration rate (μg H20/cm^2/s) of exposed, recently expanded grapevine leaves at various dates through the growing seasons. The porometer measured leaf temperature, quantum, and stomatal conductance, and from these data calculated transpiration rate (Ts). The leaves were clamped into the chamber and an ambient relative humidity was entered into the instrument. The humidity in the chamber rose due to leaf transpiration, while the instrument uses dry air to bring the humidity back to the set point (McDermitt 1990). Leaf transpiration was computed from dry air flow rate, chamber vapor pressure, leaf saturation vapor pressure, and leaf area.

Leaf transpiration rates for vines under all five treatments were measured weekly at both sites (2003 and 2004; bi-weekly in 2005). Data were taken from one block (block 2 at the Hipple site and block 4 at the Lambert site). Five exposed, recently-expanded leaves on two vines per row were selected on each vine and were measured hourly between 1100h and 1600h, giving a total of 10 readings per treatment, three times per day of measurement. The purpose of taking hourly measurements between 1100h and 1600h was to capture the peak transpiration rate, usually at midday, and to monitor how transpiration rates progressed for each treatment through the course of the day. Measurements were made 2-3 days after irrigating the treatments.

3.4- Harvest and berry sampling

Harvest occurred on 4 to 6 of September 2003, 1 to 3 September 2004, and 20 to 22 August 2005 at Lambert Farms, and 2 to 4 September 2003, 23 to 25 August 2004, and 24 to 26 August 2005 at Hipple Farms. At harvest, 100 berry samples were collected randomly from the 250 marked experimental vines at the Lambert site and 150 marked experimental vines at the Hipple site. After collection, these samples were placed in plastic bags and stored at -25°C for later analysis. An additional 300-berry sample was collected from each treatment replicate to measure concentrations of methyl anthranilate (MA) and total volatile esters (TVE) as described by Fuleki (1982).

3.4.1-Yield.

Clusters per vine were counted and yield in kilograms per vine was determined as the harvested grapes were weighed on an electronic scale within the vineyard. Cluster weight in grams was calculated from yield per vine and clusters per vine data. Berries per cluster were estimated from cluster weight and berry weight data.

3.4.2- Berry composition.

At the time for laboratory analysis, each 100-berry sample was weighed using a digital balance. Each berry sample was then placed into a 250 mL beakers heated at 80°C in in a Fisher Scientific water bath to re-dissolve tartrates that precipitated during freezing, and then blended in an Omega 9000 centrifugal juicer (Pleasant Hill Grain, Aurora, NE). Samples were then left to settle about 30 minutes before the soluble solids (Brix) were measured using an American Optical Abbé refractometer model no. 10450 (AO Corp, Buffalo, NY). The pH was measured with a Fisher Scientific Accumet pH meter model no. AB15 (Fisher Scientific, Mississauga, ON). Titratable acidity (TA) (expressed as g tartaric acid equivalents in g/L) was measured using a 5.0 mL aliquot of juice titrated with 0.1N NaOH with a PC Titrate automated titration system (Man-Tech, Guelph, ON).

3.4.3. - Berry analysis for color, anthocyanins, and phenols.

After soluble solids Brix, pH, and TA measurement, an aliquot of each juice sample was centrifuged at 6000 rpm for 10 minutes using an IEC Centra CL2 centrifuge (International Equipment Company Needham Heights, MA), placed in 20 mL plastic bottles, and stored at -25°C for later analysis for anthocyanins, color and phenols. Each sample was then filtered through a Millipore 0.45µ HV Durapore syringe membrane filter (Millipore Corp., Bedford, MA). The pH shift method was used for anthocyanin analysis. This consisted of setting up duplicate test tubes for each sample. One tube contained 9 mL of pH 1.0 buffer and the second tube contained 9 mL of pH 4.5 buffer. The buffer solutions required for anthocyanin analysis were: pH 1.0 buffer: 0.2M KCl plus 0.2M HCl; pH 4.5 buffer: 1M sodium acetate plus 1M HCl. . Exactly 1.0 mL of juice was added to each test tube and the samples were then allowed to react in the dark for one hour. The absorbance of the samples was read at 520 nm in a 10 mm glass cuvette using a Pharmacia Biotech Ultrospec 1000E UV/Vis spectrophotometer (Biochrom Ltd., Cambridge UK). Blanks of the pH buffers were used to calibrate the

spectrophotometer for each set of readings. The anthocyanin concentration (as malvidin 3,5 di-glucoside) was calculated using the formula:

Anthocyanins (mg/L) = (absorbance pH 1.0- absorbance pH 4.5) × 255.75

Color was measured by absorbance of the centrifuged juice at 420 nm (A420) and 520 nm (A520) in a 10mm glass cuvette using an Ultrospec 1000E UV/Vis spectrophotometer. In the rare event that the sample was too concentrated, it was diluted (1 mL in 9 mL) with pH 3.5 buffer. The pH 3.5 buffer consisted of 0.1M citric acid plus 0.2M Na_2HPO_4. This buffer was used as a blank to calibrate the spectrophotometer. The hue was calculated by dividing the A420 by A520, while the intensity of color was calculated from A420 + A520.

Phenols were measured using 1 mL of juice, which was added to 9 mL of distilled water, and then 1 mL of juice was added. Standards were prepared from a stock solution containing 5 g/L of gallic acid in distilled water from which five dilutions were made: 50, 100, 150, 250, and 500 mg/L. These solutions were wrapped in foil and stored in a dark cupboard. The sodium carbonate solution needed for phenols analysis was prepared as follows: 200 g of anhydrous Na_2C0_3 was added to about 700 mL of distilled water and boiled until completely dissolved. The solution was cooled at room temperature, after which 2 to 3 g of $NaC0_3$ were added. The solution was held for 24hr and filtered immediately before use. .About 60 mL of distilled water, plus 1 mL of diluted sample (or standard) were added to 100 mL volumetric flasks in duplicate for each sample. Exactly 5mL of Folin's Reagent was added to each flask and mixed for 30 seconds, after which were added 15mL of filtered Na_2C0_3 solution within 8 minutes of adding the Folin's Reagent. Samples were then mixed and brought to volume with distilled water. Solutions were left to stand in the dark for 2 hours at 20°C. The absorbance of the solutions was determined using a 10 mm glass cuvette in an Ultrospec 1000E UV/Vis spectrophotometer at 765 nm.

3.4.4. Berry analysis for methyl anthranilate (MA) and total volatile esters (TVE).

The 300 berry samples were removed from the –25°C freezer and allowed to thaw for several hours at room temperature. Samples were homogenized in a blender for 35 seconds and four sub samples of 50 g were then weighed out and distilled using the distillation apparatus pictured (Figure 7), which consists of a round bottom steam generating flask, a distillation flask, and a condensing column (Lurex, Vineland, NJ). Within Within 15 to 20 minutes, 100 mL of distillate was collected into a 100 mL volumetric flask and stored at 4°C. The same distillate was used to determine both MA and TVE concentrations.

Figure 7: Apparatus used to distill Sovereign Coronation berry samples prior to MA and TVE determination.

MA standards were prepared from a stock solution of 100 mg/L MA, which was then used to prepare eight standard solutions of concentrations ranging from 0.1 to 10 mg/L. MA concentration was determined via a luminescence spectrophotometer model no. LS50 (Perkin-Elmer, Boston, MA) that was set at an emission wavelength of 420 nm with an 8.0nm slit width, and an excitation of 325 nm and a 5.0nm slit width. The fluorescence of MA was read directly from the apparatus, while the MA concentration was determined using a standard curve.

TVE were determined through a colorimetric reaction described by Hill (1946). A 20 mL aliquot of all standards and samples in addition to distilled water blank were added to 25 mL volumetric flasks. Exactly 2.0 mL of alkaline hydroxylamine solution was then added to each flask and allowed to react for 5 minutes. This solution contained equal volumes of 6M hydroxylamine hydrochloride (made the day before analysis by weighing out 20.9 g and dissolving it in distilled water in a 50 mL volumetric flask) and 10.5N NaOH. After 5 minutes and adequate shaking, 1.0 mL of concentrated HCl was added to each flask. Following an addition of 1.0 mL 1.11M ferric chloride, the solution was brought to volume with a 0.046M ferric chloride solution. The solutions were then mixed and approximately 3 to 5 mL of sample was poured off prior to the removal of gas bubbles with repeated 15-minute vacuum purges. The flasks were shaken thoroughly between all additions of chemicals and vacuum purges. Absorbance readings of all standards and samples were carried out on a Pharmacia Biotech Ultra spec 1000E UV/Vis spectrophotometer at 540nm. Thereafter, TVE concentrations were extrapolated from the standard curve

Statistical analysis:

All data were analyzed using (SAS) statistical software SAS Institute, Cary, NC). The General Linear Models procedure (PROC GLM) was used. Duncan's multiple range comparison was used to determine where mean differences existed among treatments. Dunnett's t-test was used to determine which treatments resulted in differences from the non-irrigated control (Dunnett 1955).

Results

4.1- Irrigation scheduling.

Rainfall was highest in 2004, while in contrast, 2005 was very dry season. Therefore; the largest amount of irrigation was required in 2005 (Figure 8) Evapotranspiration rates were greatest from late June to mid-August 2005 (Figure 9) when temperatures were at their annual high and solar radiation was at its maximum. Low ET values experienced in 2004 were due to several rain events that resulted in cloudy, humid and cool conditions (Figures 9, 10). Irrigation was applied to the vines weekly (20 June to 30 August 2003 to 2005) throughout the growing seasons. Water requirements were highest in 2005 and 2003 in the early summer months due to high temperatures, and decreased as the season progressed (Figures 9, 10). Although the 2004 summer appeared to be quite wet, irrigation was still required. There were only three times when no irrigation was needed in 2003 and 2004 growing seasons because adequate amounts of water were provided to the vines by rainfall (Figure 10): once in 2003 (7 July) and twice in 2004 (7 July and 11 August).

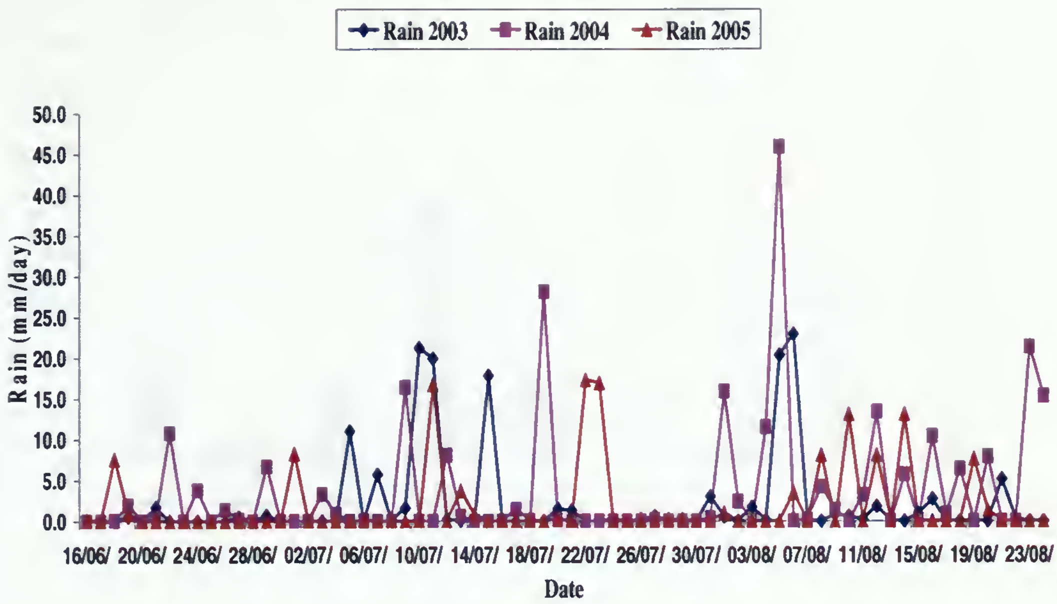

Figure 8: Daily rainfall values from June through August 2003 to 2005. Rain (mm/day) values were downloaded from OWN for the 2003-2005 growing season in Niagara-on-the-Lake.

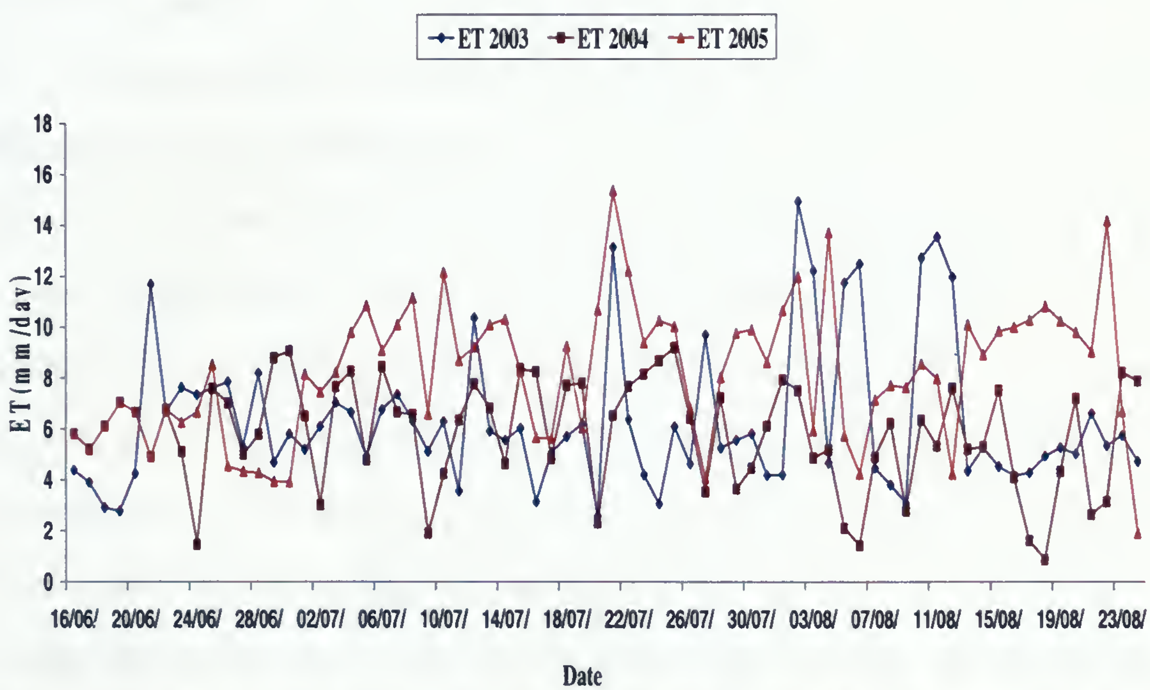

Figure 9: Daily ET evapotranspiration values from June through August 2003 to 2005. ET values were generated by the Penman-Monteith equation using weather data provided by OWN for Niagara-on-the-Lake.

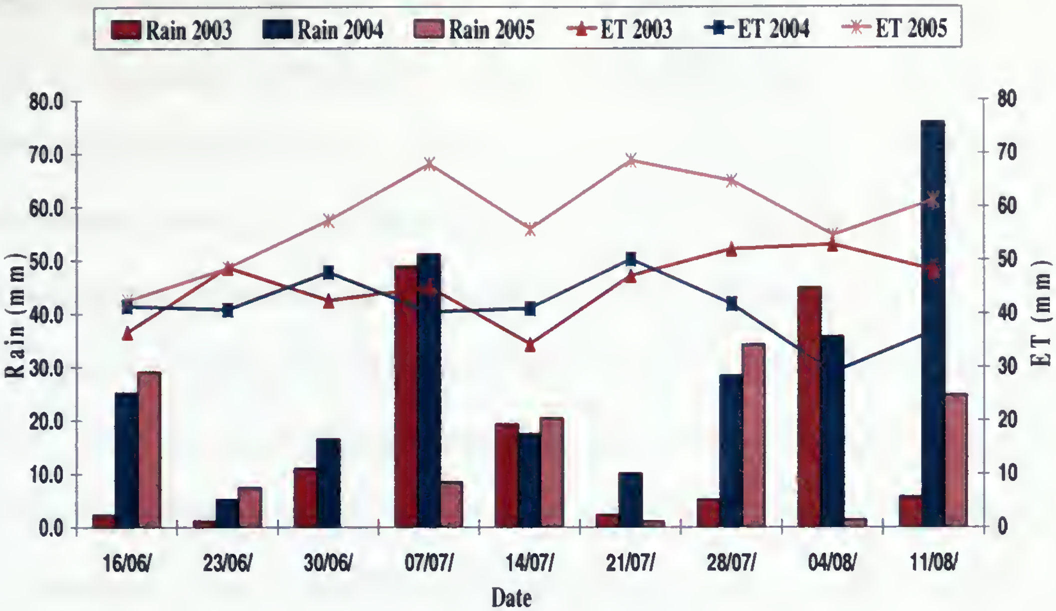

Figure 10: Weekly ET evapotranspiration and rainfall values from June through August 2003 to 2005. ET values were generated by the Penman-Monteith equation from OWN data for Niagara-on-the-Lake.

4.2- Vine and soil water status.

4.2.1- Soil moisture.

Soil moisture data were collected for each vine following a weekly irrigation throughout the 3 years of the trials. Differences in soil moisture between irrigated and non irrigated treatments were always obvious throughout the experiment, and higher moisture levels were often measured in irrigated treatments in all 3 years of the study (Figures 11 and 12). Irrigation usually supplied the vines with adequate water to maintain soil moisture levels consistently above the wilting point (13.3% and ca. 25.0% soil moisture for Lambert and Hipple, respectively) but considerably below field capacity (27.3 % and ca. 42.3 % soil moisture for Lambert and Hipple, respectively) (Kingston and Presant 1989). Plots under all treatments at both sites in 2004 showed soil moisture values that fell desirably between wilting point and field capacity at both sites; this was possibly due to the rainfall in that year (Figures 11B and 12B). Where the values recorded were between 15% to 27% at Lambert farm and 15% to 35% at

Hipple farm. High rainfall events in the 2004 growing season thus caused soil moisture levels for all the treatments including the non-irrigated treatments to increase within the available moisture range for plants. These rain events also decreased the degree of difference between the irrigated and non-irrigated treatments in that year (Figures 11B and 12B). Irrigated treatments still had higher soil moisture than non-irrigated treatments in that year.

For soil moisture at the Lambert site in 2003, all treatments were above the wilting point of 15% in all weeks, and non-irrigated treatment had the lowest value. The middle of August (19 August) had the lowest soil moisture values (Figure 11A). In 2004, the result showed that all treatments were in very good condition regarding soil moisture as all treatments had high value of moisture compared to in 2003 and 2005 seasons. This was due to the high rainfall events in the 2004 growing season that caused soil moisture levels for all the treatments including the non-irrigated treatments to increase within the available moisture range for plants. Yet, the non-irrigated treatments had the lowest moisture value (Figure 11B). Results from the 2005 growing season showed that soil moisture was higher in the irrigated treatments. The middle of the growing season had the lowest soil moisture values from 14 July to1 August but by the end of the season the soil moisture was high, which could be as a result of the rain even that occurred that week (Figure 11C). In general, 2005 the soil moisture was low relative to 2003 and 2004 growing seasons; this was a result of the very dry conditions and high temperatures in 2005 season.

Soil moisture at the Hipple site in 2003, almost all treatments were above the wilting point of 20% all season, while the non-irrigated treatment had the lowest values all season. The lowest soil moisture was recorded early in growing season, where (2 July) had the lowest soil moisture values (Figure 12A). In 2004 at the Hipple site, all treatments had high soil moisture values compared to 2003. This was due to the high rainfall events in the 2004 growing season, which caused soil moisture levels for all the treatments including the non-irrigated treatments to

increase within the available moisture range for plants. However, the non-irrigated treatments had the lowest moisture value (Figure 12B). In 2005 at the Hipple site there were 2 weeks (24 July and 1 August) where the majority of the irrigated treatments were below wilting point (Figure 12C). In those 2 weeks, the soil moisture values in irrigated treatments were as low as 6.8 % soil moisture, whereas the non-irrigated treatments were 5.2 % soil moisture. The irrigated treatments were thus still relatively higher in soil moisture content during that period compared to the non-irrigated treatment. These results offer some proof that the drip irrigated treatment rows did not add moisture in the soil around vines in nearby non-irrigated rows. These data provide evidence that Penman-Monteith scheduling of irrigation can increase soil moisture to a level above the wilting point, thus providing the vines with adequate water for their physiological needs.

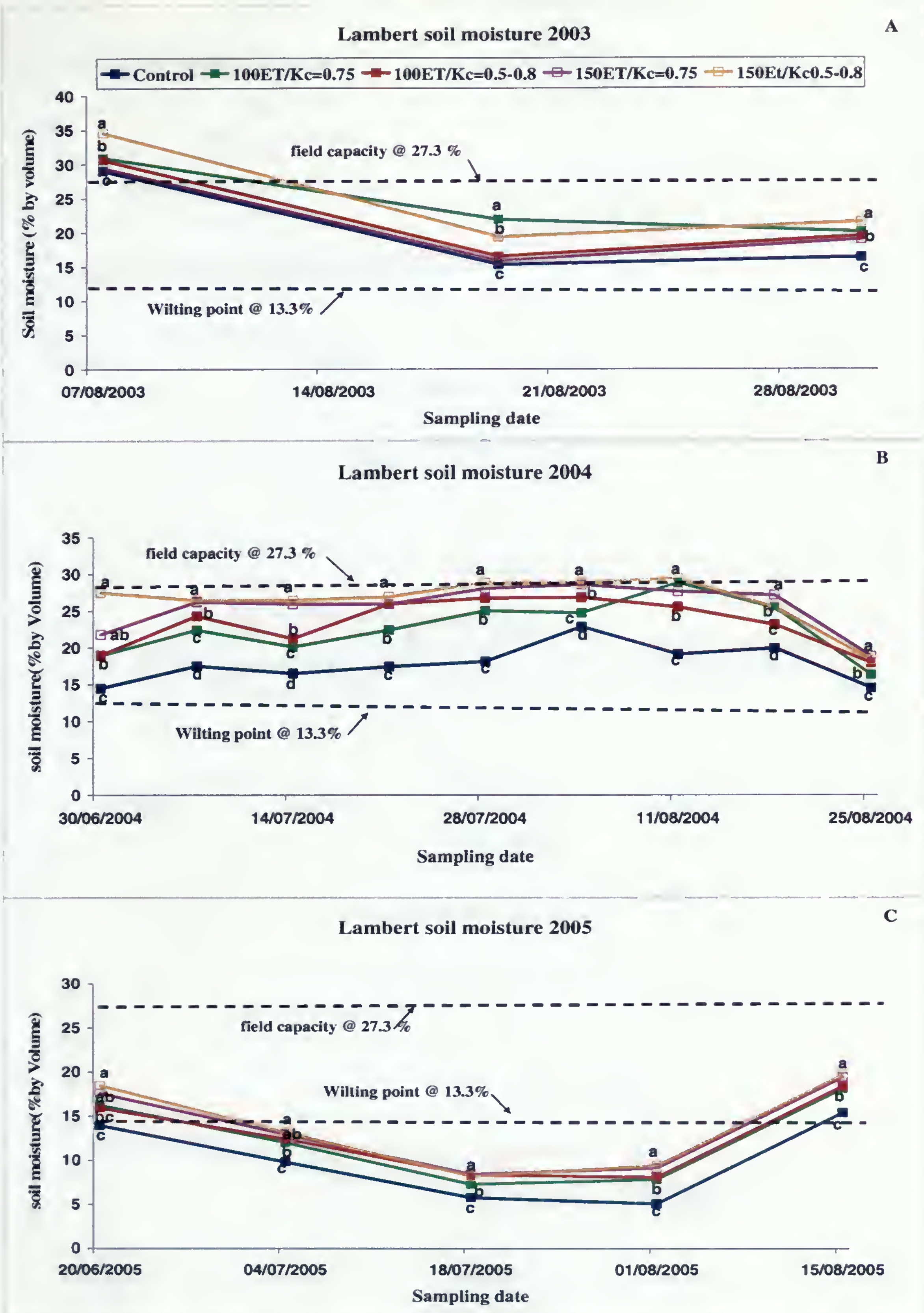

Figure 11: Impact of irrigation treatments on soil moisture (%) of Sovereign Coronation vines, Lambert Vineyards, Niagara-on-the-Lake, 2003 (A). 2004 (B), and 2005 (C). Letters represent means separated at $p \leq 0.05$, Duncan's multiple range tests.

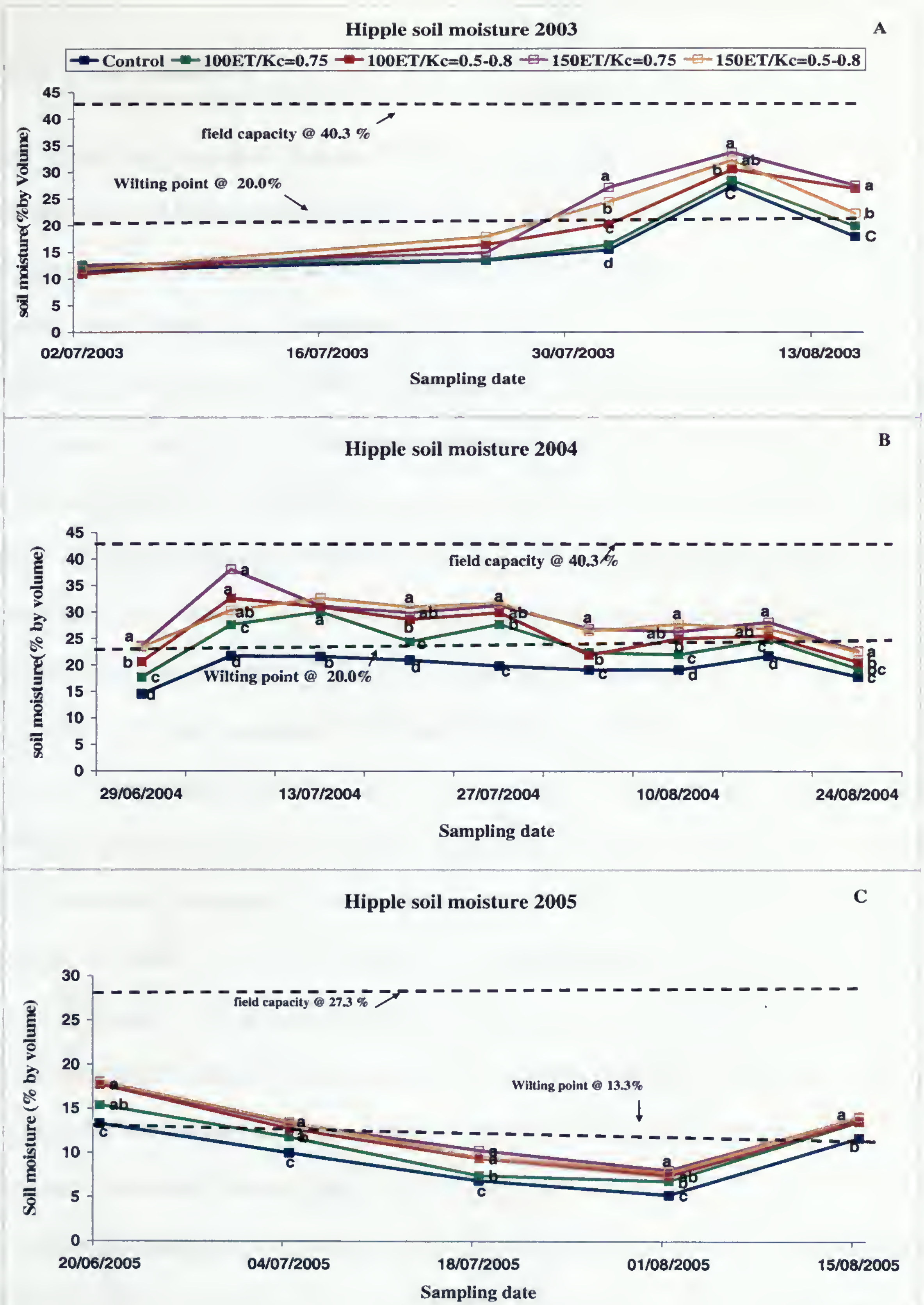

Figure 12: Impact of irrigation treatments on soil moisture (%) of Sovereign Coronation, Hipple Farms, Beamsville, ON, 2003 (A). 2004 (B), and 2005 (C). Letters represent means separated at $p \leq 0.05$, Duncan's multiple range tests.

4.2.2- Water potential.

In general, treatment differences in leaf ψ occurred at both sites in almost every week through the growing season (Figures 13 and 14). The most negative ψ were found in all treatments (< -14 bars) in the first week of 2003 at the Lambert site (Figure 13A). In fact, leaf ψ dropped to -13 bars or less for all weeks in 2003, which confirmed that water stress, was present for the vines in non-irrigated treatments (Figure 13A). Low ψ (< -12) were also found near the end of the growing season in 2004 at the Lambert vineyard under all treatments (Figure13B). In 2005, mean ψ was as low as -13 bars but only under the non-irrigated treatment, under all irrigated treatments ψ was higher than -12 bars. At the end of the growing season in 2005 ψ under all treatments had leaf ψ that was -6 or below including non-irrigated treatments, this could have been a result of the rain event that occurred that week. This agreed with soil moisture data from that week (15 August) (Figure 13C).

Differences among treatments for leaf ψ were detected in all weeks in 2003 at the Hipple site. However, the data showed that leaf ψ was very low early in the season. The non-irrigated treatment resulting in ψ as low as -16 bars (Figure 14A). The 2004 result showed that although the year was wet, somehow the absolute values of ψ were high. In this year, all treatments resulted in ψ below – 13 bars, with the non-irrigated treatment resulting in the lowest values where ψ dropped to -16 in one week (27 July) (Figure 14B). In 2005 at the Hipple site, vines that were irrigated was never below -11 bars, whereas for non-irrigated vines ψ was less than -13 bars early in the season. Hence, irrigated vines never experienced water stress, since irrigation consistently increased leaf ψ (Figure 14C).

These relationships between treatments and leaf ψ were due to increased evaporative demand that resulted from a larger canopy and the environmental conditions. In most cases, water stress was present in all treatments that were not irrigated and less evident in irrigated treatments.

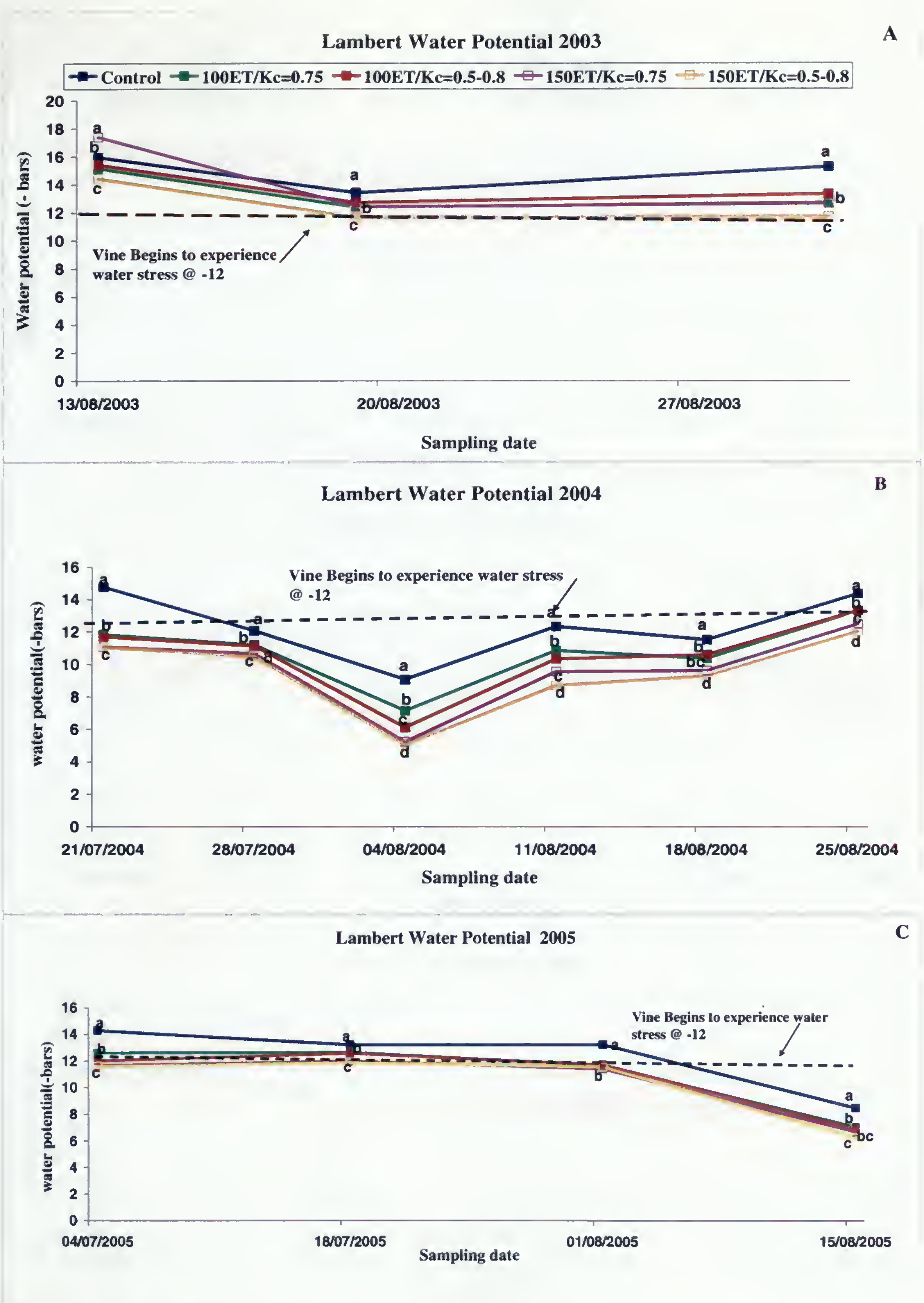

Figure 13: Impacts of irrigation on leaf water potential of Sovereign Coronation vines, Lambert Vineyards, Niagara-on-the-Lake, 2003 (A), 2004 (B), and 2005 (C) Lower case letters symbolize means separated at p<0.05, Duncan's multiple range test.

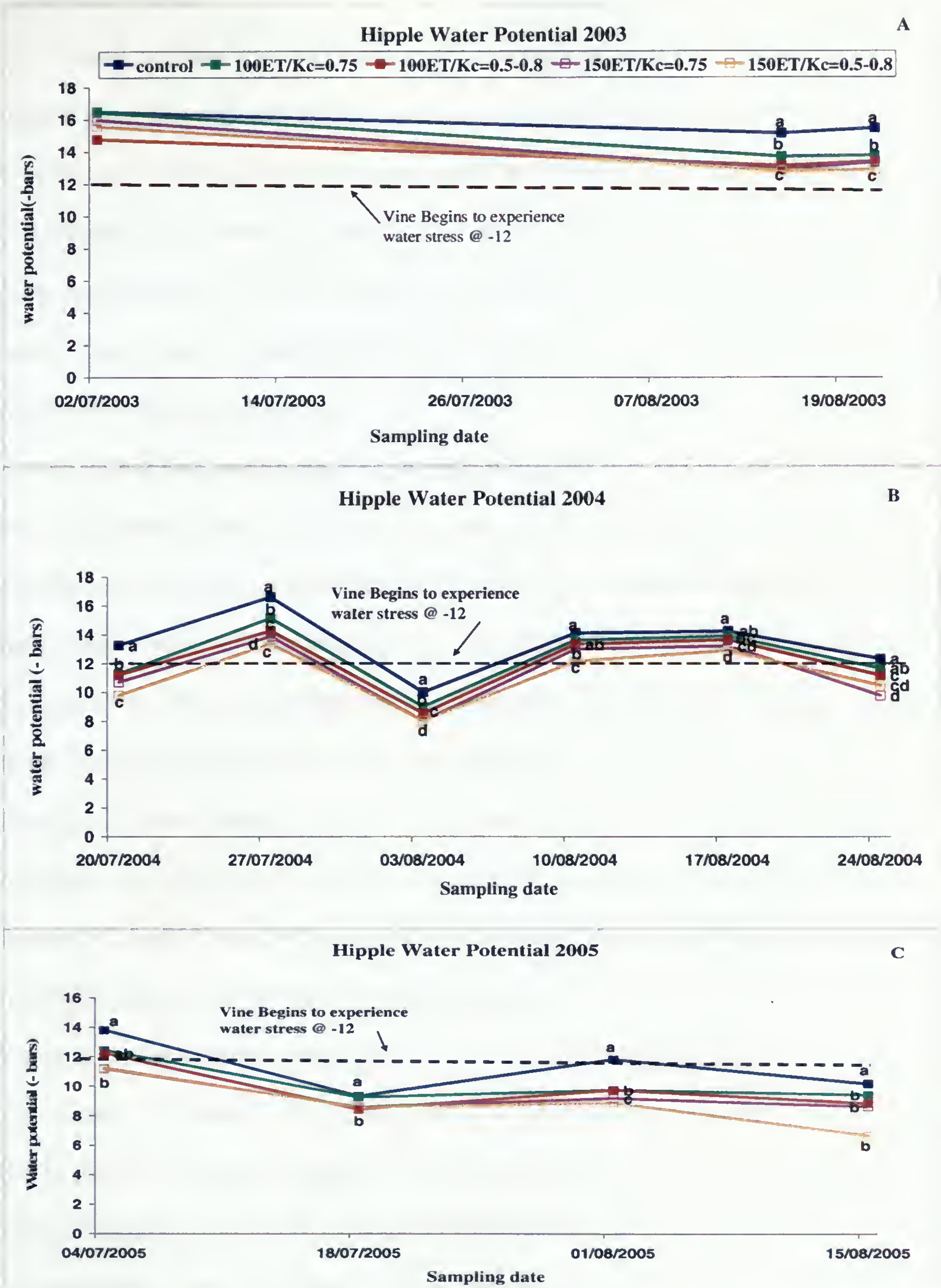

Figure 14: Impacts of irrigation on water potential of a Sovereign Coronation, Hipple Farms, Beamsville, ON, 2003, 2004, and 2005. Lower case letter symbolize means separated at $p<0.05$, Duncan's multiple range test.

4.2.3-Transpiration

Overall, irrigated vines had the greatest transpiration rates (Figures 15 and 16). The non-irrigated vines generally transpired at a lower rate than the irrigated vines. Transpiration rates in response to all treatments at both sites was higher in 2004 than in 2003 and 2005; this was due to substantial rainfall events in 2004 (Figures 15B and 16B). However, irrigated vines were still higher than control vines. This is evidence that there was water stress in non-irrigated vines. In contrast, the irrigated treatments showed highest transpiration on all dates, and in both sites, reliable with nominal water stress.

In 2003 at the Lambert site, the transpiration was low in response to all treatments, with the non-irrigated treatment resulting in the lowest value in the season (July 13), and, a trend appeared whereby the transpiration increased as the season progressed (Figure 15A). In 2004, transpiration rates for all treatments were generally higher. This was due to substantial rainfall events in 2004, although irrigated vines were still higher than control vines (Figure 15B). Data for the dry 2005-growing season suggested that the irrigation increased transpiration rates (Figure 15C). These results were evidence that there was low water status in non-irrigated treatments. In contrast, the irrigated treatments showed highest transpiration on all dates (Figure 15C). In 2003 and 2005, vines experienced a drought so severe that even supplemental irrigation could not raise transpiration levels (Figures 15Aand 15C). On 4 and 18 July and 1 August 2005 Lambert non-irrigated treatments were transpiring least (Figure 15C).

Generally, irrigated vines had the greatest transpiration rates at the Hipple site (Figures 16A to 16C). The control treatments clearly showed a consistently lower transpiration rate opposed to irrigated treatments. On 4 and 18 July 2005, Hipple (sampling dates 2 and 3) non-irrigated vines were transpiring least (Figure 16C). In 2003 at the Hipple site the transpiration was very low under all treatments, and non irrigated vines transpired the least in most weeks, with the lowest value early in the season (4 July); however, there were no differences between

irrigated and non irrigated vines in that week. In addition, this season showed a trend where the transpiration increased as the season progressed with evidence that non-irrigated vines transpired least (Figure 15C). In 2004, transpiration rates for all treatments were higher. This was due somewhat to substantial rainfall events in 2004, but irrigated treatments were still higher than control treatments (Figure 16B). Data for the 2005 growing season showed that irrigation increased transpiration rates. All treatments resulted in low transpiration rates in the mid- season. By the end of the season all treatments resulted in high transpiration rates and the non-irrigated treatment always resulted in the lowest transpiration rates. These results indicated that there was low water status in non-irrigated treatments (Figure 16C).

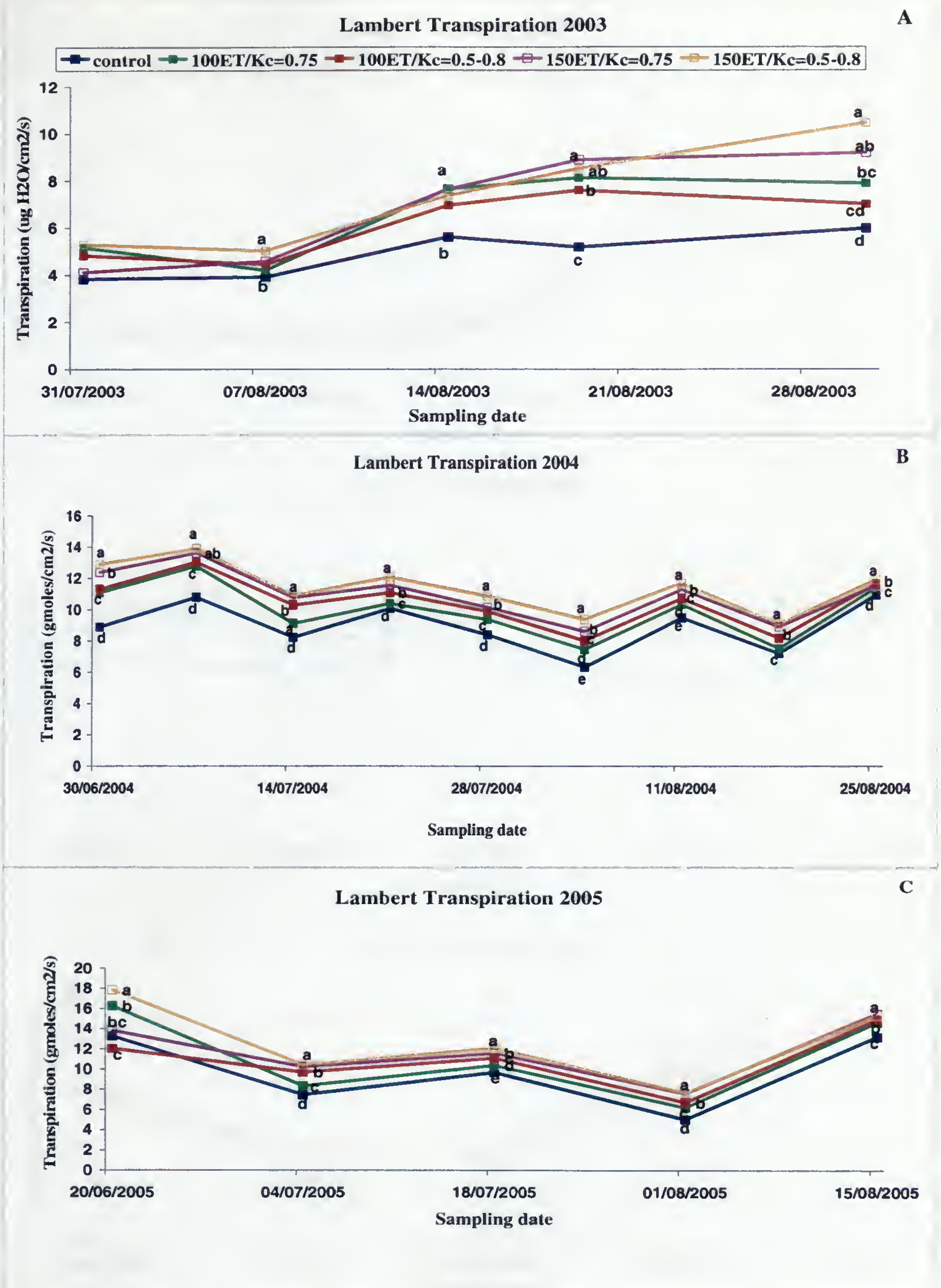

Figure 15: The impact of irrigation treatments on leaf transpiration of Sovereign Coronation table grapes, Lambert Vineyards, Niagara-on-the-Lake, summer 2003 (A), 2004 (B), and 2005 (C). Lower case letter symbolize means separated at $p<0.05$, Duncan's multiple range test.

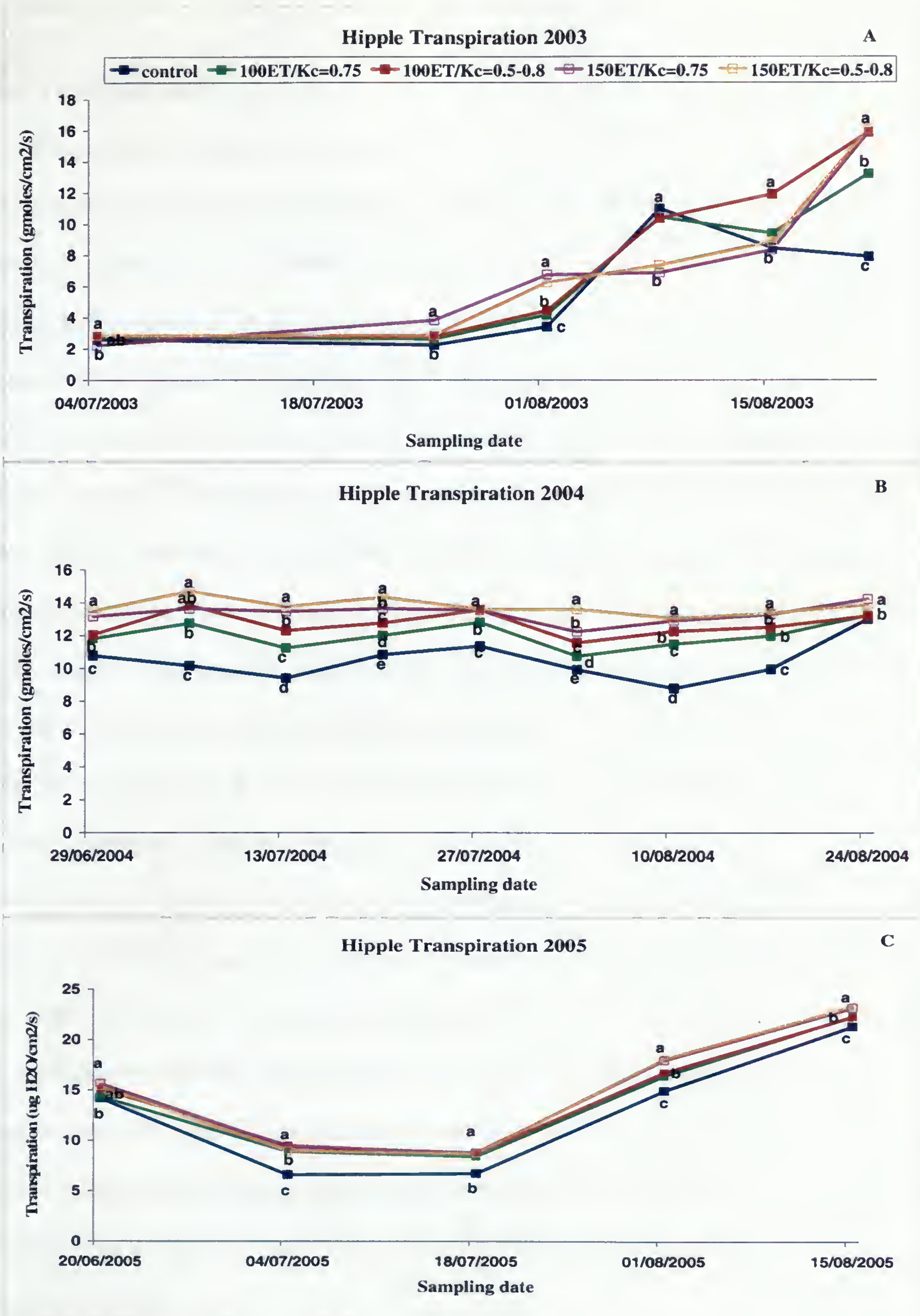

Figure 16: The impact of irrigation treatments on leaf transpiration of Sovereign Coronation table grapes, Hipple Farms, Beamsville, ON, 2003(A), 2004 (B), and 2005 (C). Lower case letter symbolize means separated at p<0.05, Duncan's multiple range test.

4.3- Yield components.

Irrigation had a considerable positive effect on yield in 2005 but not in 2003 or 2004. A yield was increased in 2005 by all irrigation treatments at the Lambert site, whereby yield increased by about 10 to 27%, relative to the non- irrigated treatment, with the 150ET treatments yielding highest (Table 2). A similar trend was found in 2005 at the Hipple site where the irrigated treatments had 6 to 30% higher yields relative to the non-irrigated treatment, with the 150ET treatments being superior. Clusters per vine showed a positive response to irrigation in 2005 at both sites. Clusters per vine at the Lambert site increased by 13 to 27% in irrigated treatments, with the 150ET treatments being superior. Clusters per vine at the Hipple site were increased in irrigated treatments by 8 to 22%, with the 150ET treatments again being superior. Cluster weight was increased in irrigated treatments over non-irrigated treatment. In 2003 at the Lambert site there was a trend for all irrigated treatments to exceed the control (3 to 19% increases), although only the 100ET/0.5-0.8 treatment was significantly different. Cluster weights were not affected by irrigation at the Lambert site in 2004 or 2005. The Hipple site, however, showed increases in cluster weights in two of four irrigated treatments in 2003 and one of four in 2005; the 150ET treatments were increased by about 18 to 19% relative to the non-irrigated treatment in 2003, and all the irrigated treatments showed a increasing trend (5 to13%) relative to the non-irrigated treatment. Although there were some differences among treatments at the Lambert site in 2004 and 2005, there were no obvious benefits of irrigation in terms of berries per cluster. The same could be said of the irrigation treatments at the Hipple site in 2003 and 2004, but there was a 24% increase in 2005 in response to 150ET/0.75 treatment relative to the non-irrigated treatment.

Table2: Impact of irrigation treatments on yield components and berry composition of Sovereign Coronation table grapes, Lambert Farms, Niagara-on-the-Lake, ON, 2003 to 2005. *,,***,****, 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 tests. Boldfaced data indicate those values significantly different from the control, Dunnett's t-test.**

Treatment	Yield/vine (kg)			Clusters/vine			Cluster wt. (g)			Berries/cluster		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Control	8.1	11.4	6.9d	41	69	40b	196.9b	159.7	177.8	66	58a	45b
100ET/ K_c =0.75	7.6	12.2	7.7c	38	72	46b	203.3b	162.1	170.8	69	53ab	45b
100ET/ K_c =0.5-0.8	8.4	12.2	8.5b	39	70	50b	**240.2a**	**171.2**	176.1	**81**	59a	46b
150ET/ K_c =0.75	7.6	12.1	**9.3a**	36	68	**54a**	**210.1ab**	**187.9**	174.6	69	56a	**53a**
150ET/ K_c =0.5-0.8	**8.8**	11.9	**9.4a**	41	70	**53a**	**211.6ab**	160.1	175.9	**87**	42b	46b
Significance	ns	ns	****	ns	ns	****	*	ns	ns	ns	**	**

Table3: Impact of irrigation treatments on yield components of Sovereign Coronation table grapes, Hipple Farms, Beamsville, ON, 2003 to 2005.. *,,***,****, 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 tests. Boldfaced data indicate those values significantly different from the control, Dunnett's t-test.**

Treatment	Yield/vine (kg)			Clusters/vine			Cluster wt. (g)			Berries/cluster		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Control	6.3a	10.2a	5.9d	57a	96a	47c	109.8b	105.0a	125.2b	51a	46a	40b
100ET/ K_c =0.75	5.9a	8.5c	6.3cd	50b	81b	51b	107.1b	102.8ab	133.8ab	42b	46a	41b
100ET/ K_c =0.5-0.8	4.8b	7.6c	7.0bc	45b	79b	**54ab**	100.8b	93.7c	131.5ab	37c	45ab	45b
150ET/ K_c =0.75	6.5a	9.4ab	**7.7ab**	48b	94a	**58ab**	**134.3a**	98.1bc	134.6ab	48a	44b	**53a**
150ET/ K_c =0.5-0.8	**6.8a**	8.8b	**8.5a**	49b	90a	**60a**	**136.0a**	97.2bc	**144.1a**	49a	45ab	43b
Significance	****	**	**	***	****	****	****	**	****	****	*	***

4.4 Vine size

Weight of cane prunings (kg/vine) was increased by the irrigated treatments in 2003 at Lambert and in 2003 and 2004 at Hipple. At the Lambert site, the control treatments were lowest in pruning weight, while the irrigated treatments pruning weight were increased (37 to 74%) than non- irrigated treatment (Figure 17). The same general trend was apparent at the Hipple site in 2003 and 2004 (Figure 18).

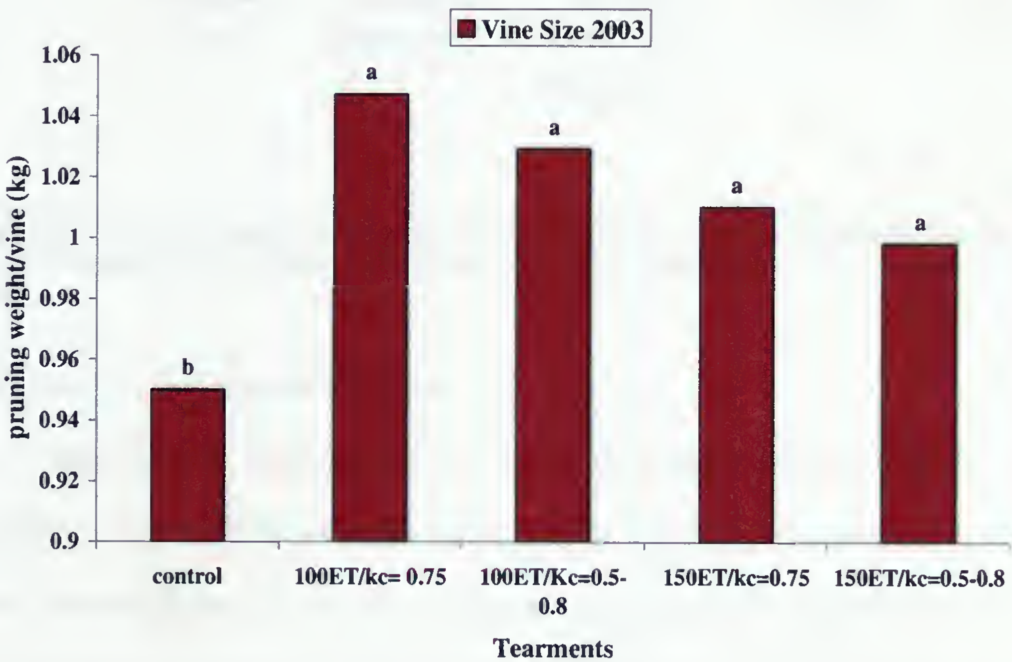

Figure 17: Impact of irrigation treatments on vine size (kg) of Sovereign Coronation table grapes, Lambert Vineyard, Niagara-on-the-Lake, ON, 2003. Letters represent means separated at $p \leq 0.05$, Duncan's multiple range tests.

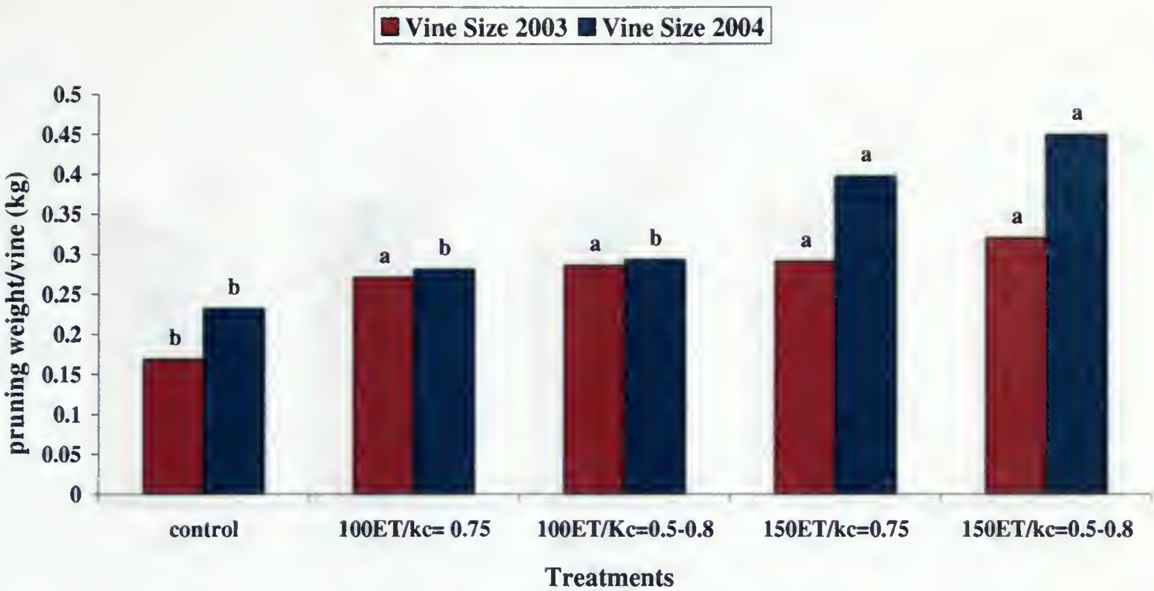

Figure18: Impact of irrigation treatments on vine size (kg) of Sovereign Coronation table grapes,, Hipple Farms, Beamsville, ON, 2003-04. Letters represent means separated at $p \leq 0.05$, Duncan's multiple range tests.

4.5- Berry weight and composition.

Berry weight. Irrigation had positive effects on berry weight at both sites, whereby the irrigated treatments were generally higher in berry weight than non-irrigated treatment for all three seasons (Figures 19, 20). At the Lambert site, the berry weight was increased 10 to 14% by the irrigated treatments in both 2004 and 2005 relative to non-irrigated treatments (Figure 19). There were no effects on berry weight in 2003 at the Lambert site. At the Hipple site, irrigation increased berry weights by 16 to 23% over non-irrigated treatment in 2003, by 11 to 16% in 2004, and by 15 to 29% in 2005 (Figure 20). In practically each case, the 150ET treatments produced highest berry weights.

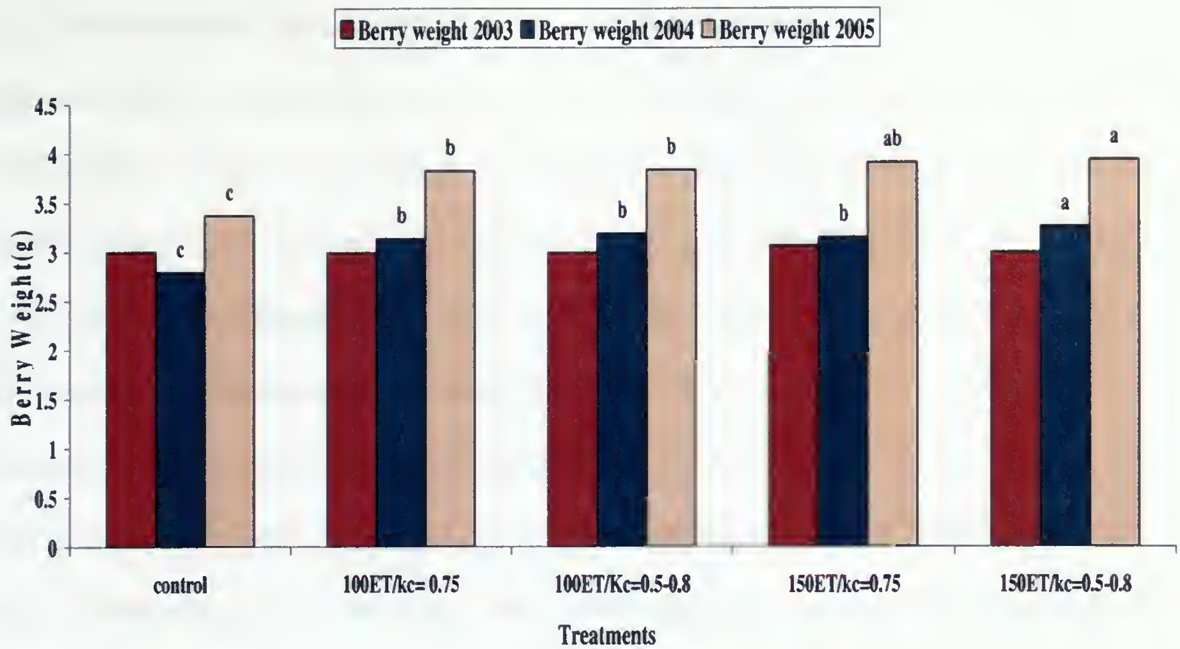

Figure 19: Impact of irrigation treatments on berry weight (g) of Sovereign Coronation table grapes, Lambert Vineyard, Niagara-on-the-Lake, ON, 2003 to 2005. Letters represent means separated at $p \leq 0.05$, Duncan's multiple range tests.

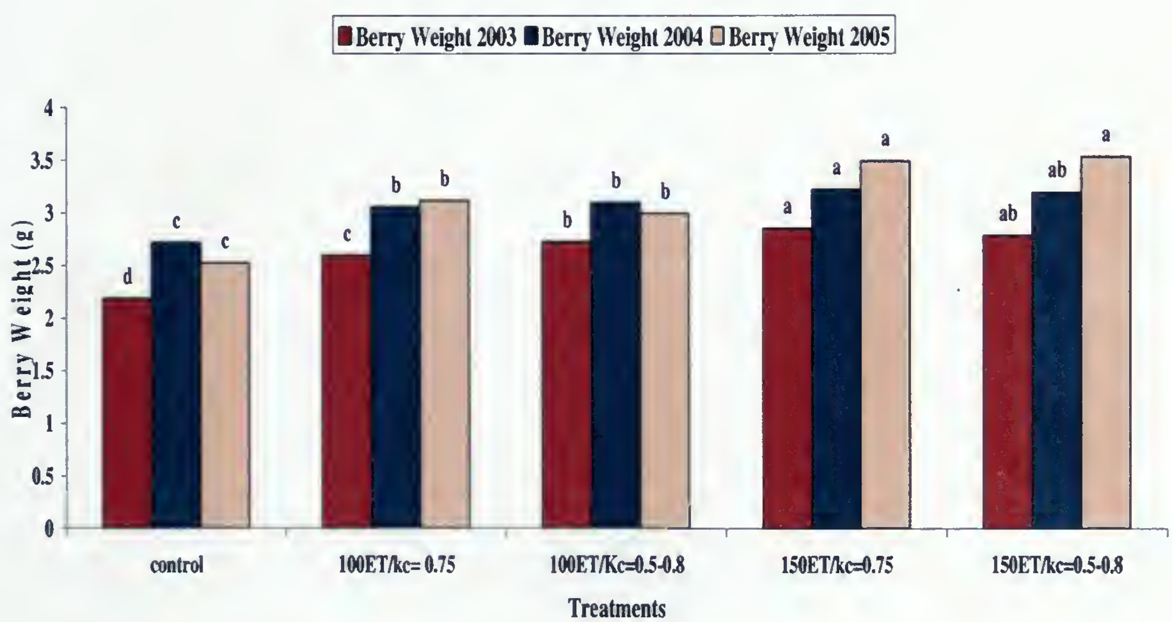

Figure 20: Impact of irrigation treatments on berry weight (g) of Sovereign Coronation table grapes, Hipple Farms, Beamsville, ON, 2003 to 2005. Letters represent means separated at $p \leq 0.05$, Duncan's multiple range test.

Soluble solids. Juice soluble solids (SS) levels were generally higher in irrigated treatments than in non-irrigated treatments for all 3 years at the Lambert site (Figure 21). The 150ET/0.75 treatment was the highest in 2003 but the other 150ET treatment resulted in lowest soluble solids (SS) in the same year. In 2004, the control treatment had the lowest in Brix, and two of four irrigated treatments exceeded it. The same trend was found in 2005 at the Lambert site, where all irrigated treatments produced soluble solids (SS) higher than the non-irrigated treatment. The same trend was also found at the Hipple site, where an increase in soluble solids (SS) by irrigation treatments over the control was observed in 2004 and 2005 (Figure 22). The highest soluble solids (SS) was found in the 150ET treatments, and specifically in 2004, where the berries measured 22 Brix under the 150ET/0.5-0.8 treatment.

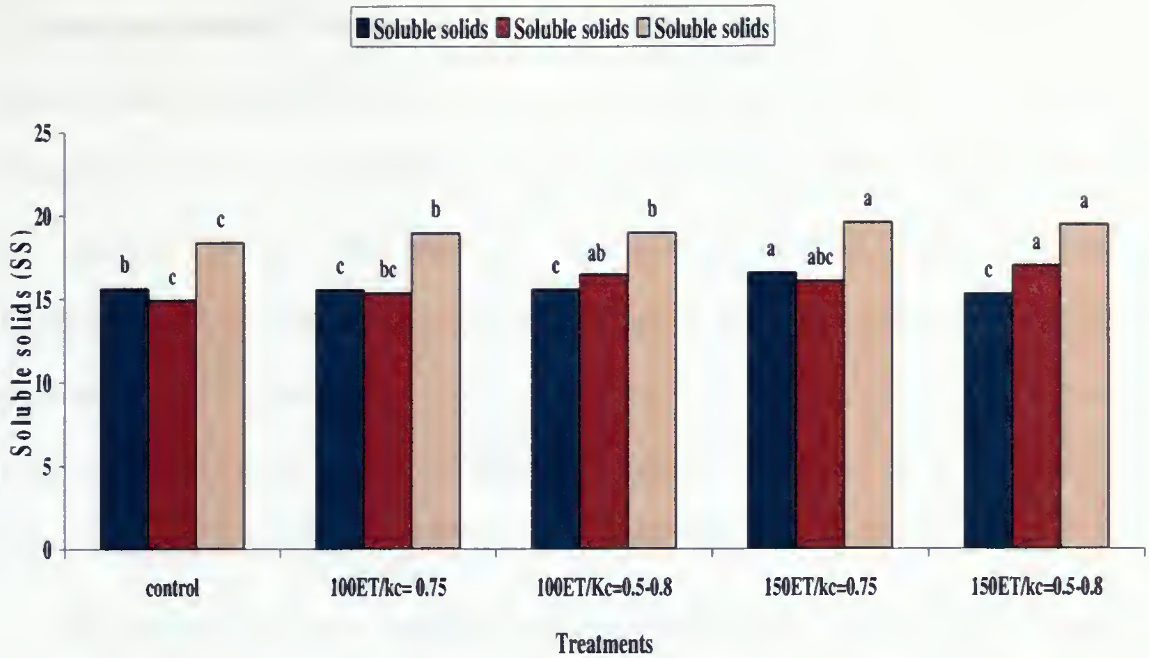

Figure 21: Impacts of irrigation treatments on soluble solids (Brix), of Sovereign Coronation table grapes, Lambert Vineyards, Niagara-on-the-Lake, 2003 to 2005. Lower case letters symbolize means separated at $p \leq 0.05$, Duncan's multiple range test.

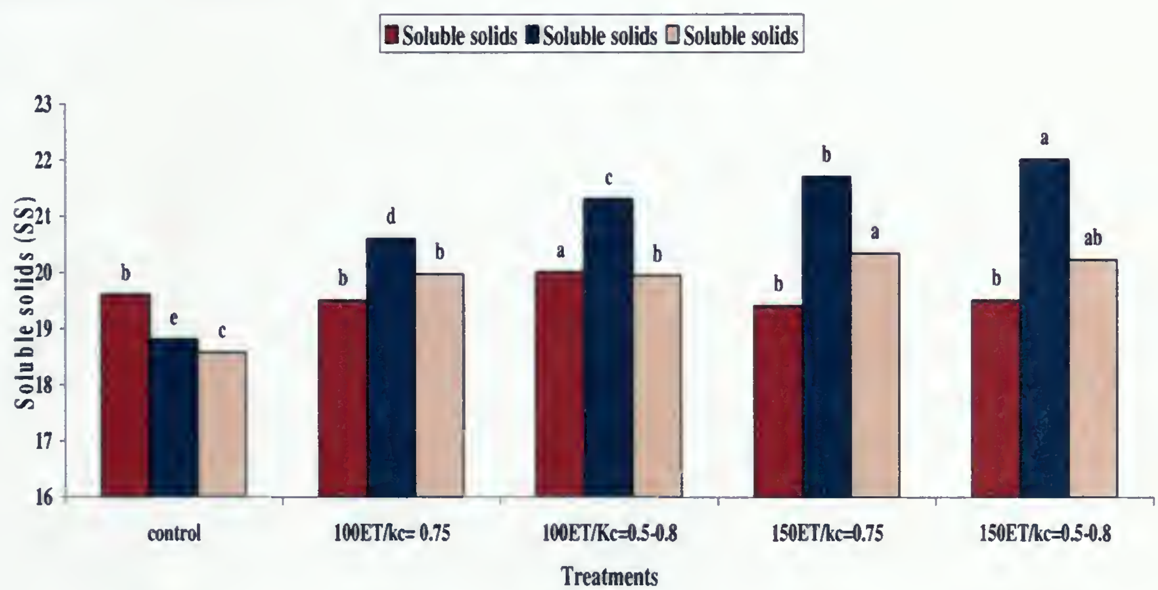

Figure 22: Impacts of irrigation treatments on soluble solids (Brix), of Sovereign Coronation table grapes, Hipple Farms, Beamsville, ON, 2003 to 2005. Lower case letters symbolize means separated at $p \leq 0.05$, Duncan's multiple range test.

Titratable acidity. Titratable acidity (TA) increased in response to two irrigated treatments both with kc 0.5 to 0.8 in 2003 at the Lambert site but was decreased by irrigation in 2004 and 2005 (Table 4). The 150ET treatments resulted in the lowest TA level in 2004 and 2005. The lowest TA across all 3 years was measured in 2004 in the 150ET-/0.5-0.8 treatment (11.8 g/L). The Hipple site, on the other hand, had lowest TA in the control treatment in the 2003 season, which was coincidentally the lowest measured TA across all 3 years at that site (11.2 g/L; compared to 14.1 g/L in the 100Et/0.75 treatment that year). As at Lambert, TA was lowest in response to irrigation in 2004 and 2005 at the Hipple site (Table 5).

pH. pH at the Lambert site was little affected by irrigation in 2003 (Table 4). However, in 2004, all irrigated treatments caused a slight decrease in pH relative to the control, whereas in 2005, the pH increased in response to irrigation. The same general trend occurred as well at the Hipple site in 2004 and 2005 (Table 5). However, in 2003 pH decreased in response to irrigation as in 2004 as well.

Table4: Impact of irrigation treatments on titratable acidity and pH of Sovereign Coronation table grapes, Lambert Farms, Niagara-on-the-Lake, ON, 2003 to 2005. Means followed by different letters are significant at $p < 0.05$, Duncan's multiple range tests. *,*, ****, ns: significant at $p < 0.05$, 0.001, 0.0001, or not significant, respectively.**

Treatment	Titratable acidity (g/L)			pH		
	2003	2004	2005	2003	2004	2005
Control	15.5 b	13.4 a	16.1 a	3.18 a	3.31 a	3.22 d
100ET/ Kc=0.75	15.2 b	12.7 b	15.7 b	3.17 ab	3.26 b	3.30 c
100ET/ Kc=0.5-0.8	16.3 a	12.5 b	15.6 b	3.15 b	3.27 b	3.33 b
150ET/ Kc=0.75	14.5 c	12.0 c	15.0 c	3.17 ab	3.22 c	3.36 ab
150ET/ Kc=0.5-0.8	16.1 a	11.8 c	14.9 c	3.16 ab	3.23 c	3.38 a
Significance	***	****	***	*	***	***

Table5: Impact of irrigation treatments on titratable acidity and pH of Sovereign Coronation table grapes, Hipple Farms, Beamsville, ON, 2003 to 2005. Means followed by different letters are significant at $p < 0.05$, Duncan's multiple range tests. *, **, *, ****: significant at $p < 0.05$, 0.01, 0.001, or 0.0001, respectively.**

Treatment	Titratable acidity (g/L)			pH		
	2003	2004	2005	2003	2004	2005
Control	11.2 c	13.3 a	13.4 a	3.16 a	3.22 a	3.16 c
100ET/ Kc=0.75	14.1 a	12.3 b	13.1 b	3.14 b	3.19 b	3.27 b
100ET/ Kc=0.5-0.8	12.9 b	12.5 b	12.7 c	3.12 c	3.18 b	3.27 b
150ET/ Kc=0.75	12.7 b	11.9 c	12.2 d	3.07 d	3.15 c	3.31 a
150ET/ Kc=0.5-0.8	13.0 b	11.6 d	12.2 d	3.07 d	3.16 c	3.33 a
Significance	****	****	***	***	****	****

Color. In general, hue increased under the irrigated treatments in both sites in all three seasons of study (Tables 6 and 7). This increase was more pronounced during 2003 at the Lambert site where the 150ET/.75 treatment resulted in the maximum value attained (0.95), whereas the control hue was only 0.58 in the same growing season. Two of four and three of four irrigation treatments exceeded the control in 2004 and 2005, respectively. At the Hipple site, two of four irrigation treatments exceeded the control in terms of hue in 2003, and only one (150ET/0.5-0.8) was higher here in each of the following two seasons (Table 7). The hue values of grapes from the Lambert vines tended to be slightly higher than the vines from Hipple vines (Tables 6 and 7).

Color intensity followed an increasing trend with some irrigation in 2004 and 2005 but not 2003. At the Lambert site, color intensity in response to the 150ET/0.75 exceeded the control in 2003, but other irrigated treatments were lower (Table 6). No effects were noted in 2004, while in 2005, three of four irrigated treatments exceeded the control. At the Hipple site, the control exceeded all irrigated treatments in color intensity in 2003, but one treatment (150ET/0.5-0.8) exceeded the control in 2004, while all irrigated treatments exceeded the control in 2005 (Table 7). The intensity values for the Hipple site were slightly higher than the values for Lambert farm vines over the three growing seasons.

Anthocyanins. Irrigation also had an effect on anthocyanin accumulation. In the 2003 season the control treatment experienced the highest anthocyanin accumulation at both sites, while the 150/0.75 ET and the 100ET/0.5-0.8 treatments were the second-highest in anthocyanins at Lambert and Hipple, respectively (Tables 6 and 7). The control exceeded the irrigated treatments in 2004 at Lambert also, but two treatments (both 150ET) exceeded the control in 2005. At the Hipple site, three of four irrigated treatments exceeded the control in 2004 and 2005. The total anthocyanins therefore showed increasing trends for the 2005 season in irrigated treatments at both sites and in 2004 at the Hipple site. In 2003, anthocyanin

concentrations from Lambert vines were higher than the vines from Hipple vines in all treatments but the control.

Total phenols. Total phenols increased in response to most irrigated treatments in 2003 and 2004 growing seasons at both sites. At the Lambert site, two of four irrigated treatments exceeded the control in 2003, and all four were higher in 2005; the same pattern was evident at the Hipple site (Tables 6 and 7). Total phenols concentrations in the grapes from Hipple vines were higher than the vines observed from Lambert vines.

Table6: The impact of irrigation treatments on anthocyanins, phenols, intensity, and hue of Sovereign Coronation table grapes, Lambert Farms, Niagara-on-the-Lake, ON, 2003-05. *, **, *, ****: Significant at p< 0.05, 0.01, 0.001, or 0.0001, respectively. Lower case letter symbolize means separated at p≤0.05, Duncan's multiple range test.**

Treatment	Anthocyanins (mg/L)			Phenols (mg/L)			Intensity			Hue		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Control	**389.1a**	**392.1a**	302.9b	916.5d	**1186.9c**	**1614.8a**	11.18b	8.23	10.96c	0.58d	0.55c	0.59b
100ET/ K_c =0.75	340.7c	329.3c	303.7b	1067.6c	1171.3c	1589.5b	10.23d	11.73	11.27bc	0.74b	**0.59a**	**0.67a**
100ET/ K_c =0.5-0.8	365.9b	232.3c	327.7b	1122.9b	1157.6c	1485.9c	10.54c	10.04	11.75b	0.59d	0.56abc	0.60b
150ET/ K_c =0.75	388.1ab	321.0c	**359.5a**	1281a	1224.3b	1266.3d	**12.33a**	11.93	**12.66a**	**0.95a**	**0.58ab**	**0.66a**
150ET/ K_c =0.5-0.8	347.5c	374.9b	**367.3a**	1144.6b	**1299.4a**	**1453.6c**	9.91e	10.72	**12.84a**	0.64c	**0.53 c**	**0.71a**
Significance	***	**	**	****	*	***	****	ns	***	***	*	***

Table7: The impact of irrigation treatments on anthocyanins, phenols, Intensity, and hue of Sovereign Coronation table grapes, Hipple Farms, Beamsville, ON, 2003-05. *, **, *, ****: Significant at p< 0.05, 0.01, 0.001, or 0.0001, respectively. Lower case letter symbolize means separated at p≤0.05, Duncan's multiple range test.**

Treatment	Anthocyanins (mg/L)			Phenols (mg/L)			Intensity			Hue		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Control	**399.8a**	341.1c	313.6d	1623.3d	1492.7c	**1935.5a**	**21.83a**	19.79b	17.77c	0.47c	0.37b	0.48b
100ET/ K_c =0.75	288.2c	349.5c	331.7cd	1747.7ab	1597.2b	**1916.2a**	20.07c	23.25b	19.11b	0.50b	0.41ab	0.52ab
100ET/ K_c =0.5-0.8	337.6b	358.8b	356.4bc	**1855.1a**	**1885.3a**	1884.5b	21.19b	20.56b	**20,31a**	0.48c	0.40ab	0.49ab
150ET/ K_c =0.75	232.3d	370.0b	384.1ab	1411.1c	1416.3c	1834.8b	18.33d	25.23ab	19.53ab	**0.56a**	0.43ab	0.50ab
150ET/ K_c =0.5-0.8	281.7c	**389.3a**	**397.1a**	1669.6ab	1574.6d	1752.6c	21.84b	**28.57a**	19.41b	0.48c	**0.52a**	**0.53a**
Significance	****	***	***	*	****	***	**	**	****	**	*	****

Aroma compounds. Methyl anthranilate. Methyl anthranilate (MA) was increased by most irrigated treatments in the three growing seasons at both sites (Figures 23 and 24). Specifically, at the Lambert site, four of four irrigation treatments exceeded the control in 2003, 2004, and 2005. The150 ET treatments typically resulted in the highest MA. At the Hipple site, three of four irrigation treatments exceeded the control in 2003, 2004 and 2005. Again, the 150ET treatments had the highest MA values in the 2004 and 2005 seasons. In general, non-irrigated treatments tended to be lower in MA accumulation over the three growing seasons.

Total volatile esters. Total volatile esters (TVE) were generally higher in response to irrigation in 2004 and 2005 at the Lambert site (Figure 25). This trend was also found in the Hipple site in the 2004 and 2005 seasons where the irrigated treatments had the highest TVE values, whereas in 2003 both the control and 150ET/0.5-0.8 treatments had the lowest TVE values (Figure 26).

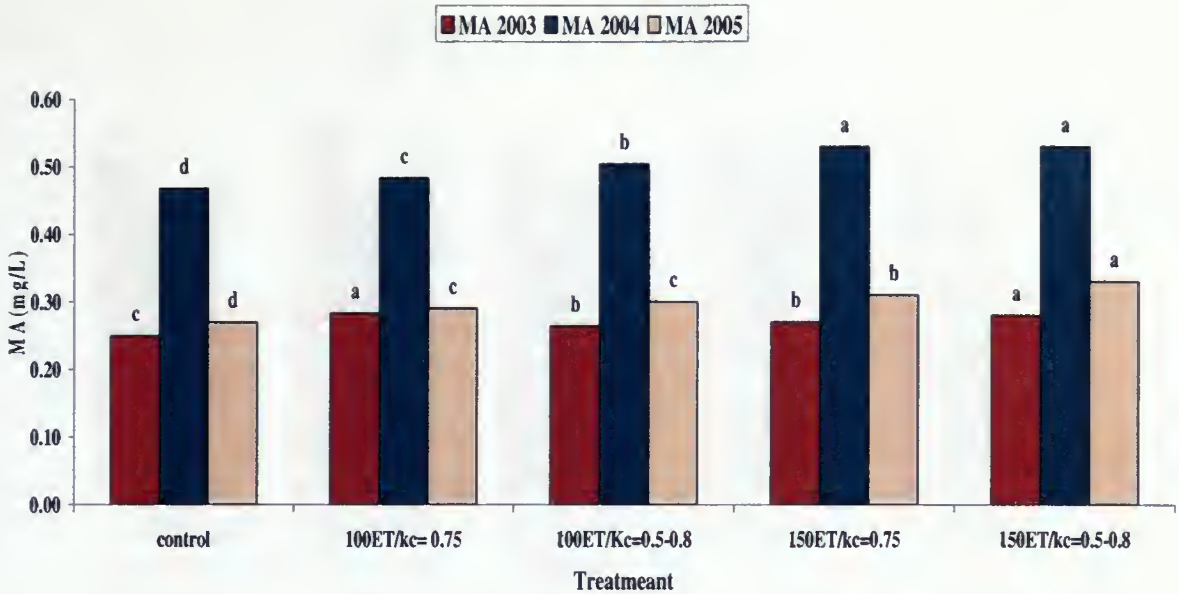

Figure 23: Impact of irrigation treatments on MA of Sovereign Coronation table grapes, Lambert Vineyards, Niagara-on-the-Lake, 2003 to 2005. . Lower case letter symbolize means separated at $p \leq 0.05$, Duncan's multiple range test.

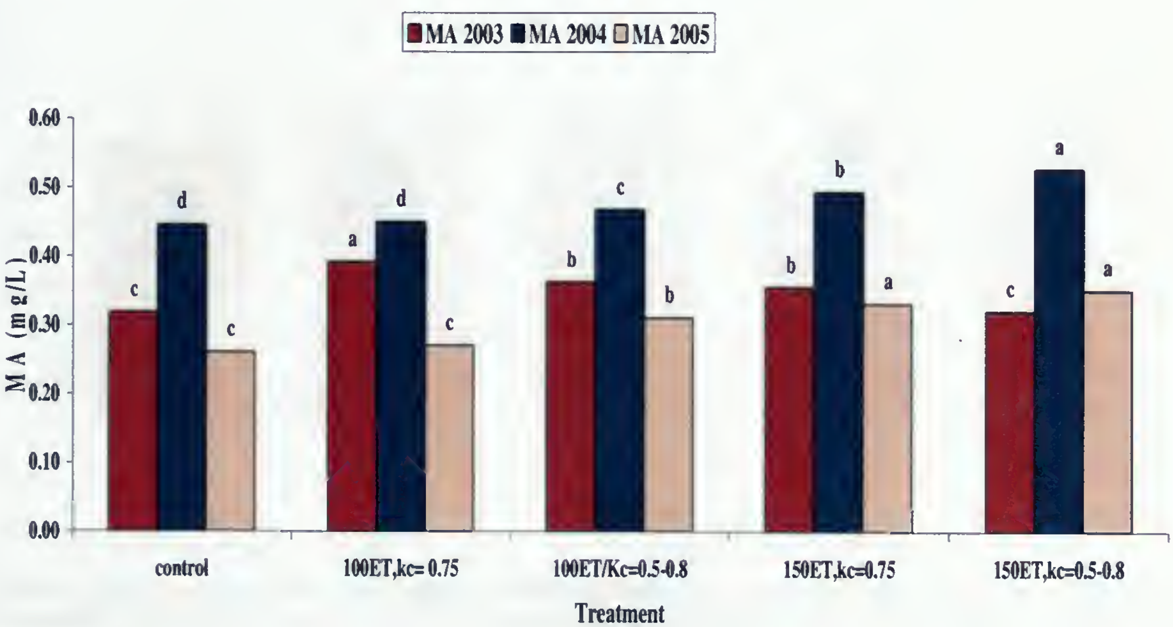

Figure 24: Impact of irrigation treatments on MA of Sovereign Coronation table grapes, Hipple Farms, Beamsville, ON, 2003 to 2005. Lower case letter symbolize means separated at $p \leq 0.05$, Duncan's multiple range test.

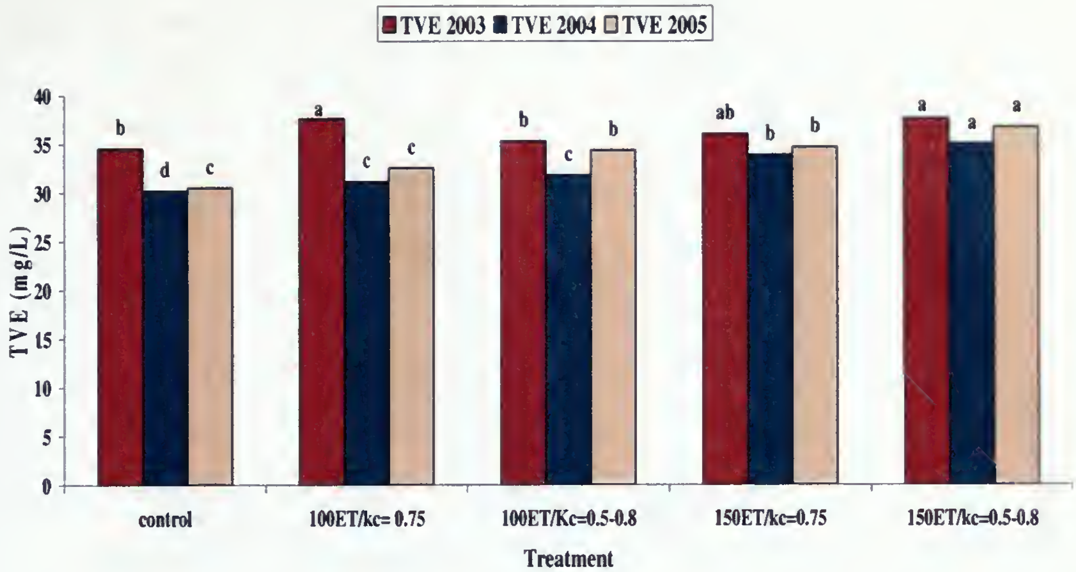

Figure 25: Impacts of irrigation treatments on TVE, of Sovereign Coronation table grapes, Lambert Vineyards, Niagara-on-the-Lake, 2003 to 2005.. Lower case letter symbolize means separated at p≤0.05, Duncan's multiple range test.

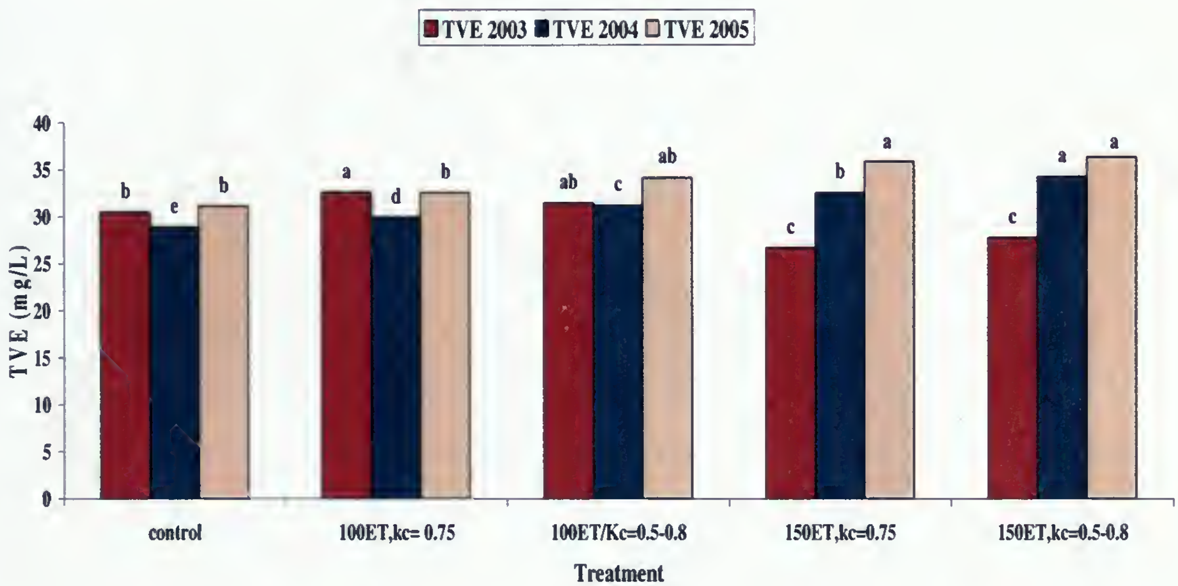

Figure 26: Impacts of irrigation treatments on TVE of Sovereign Coronation table grapes, Hipple Farms, Beamsville, ON, 2003 to 2005. Lower case letter symbolize means separated at p≤0.05, Duncan's multiple range test.

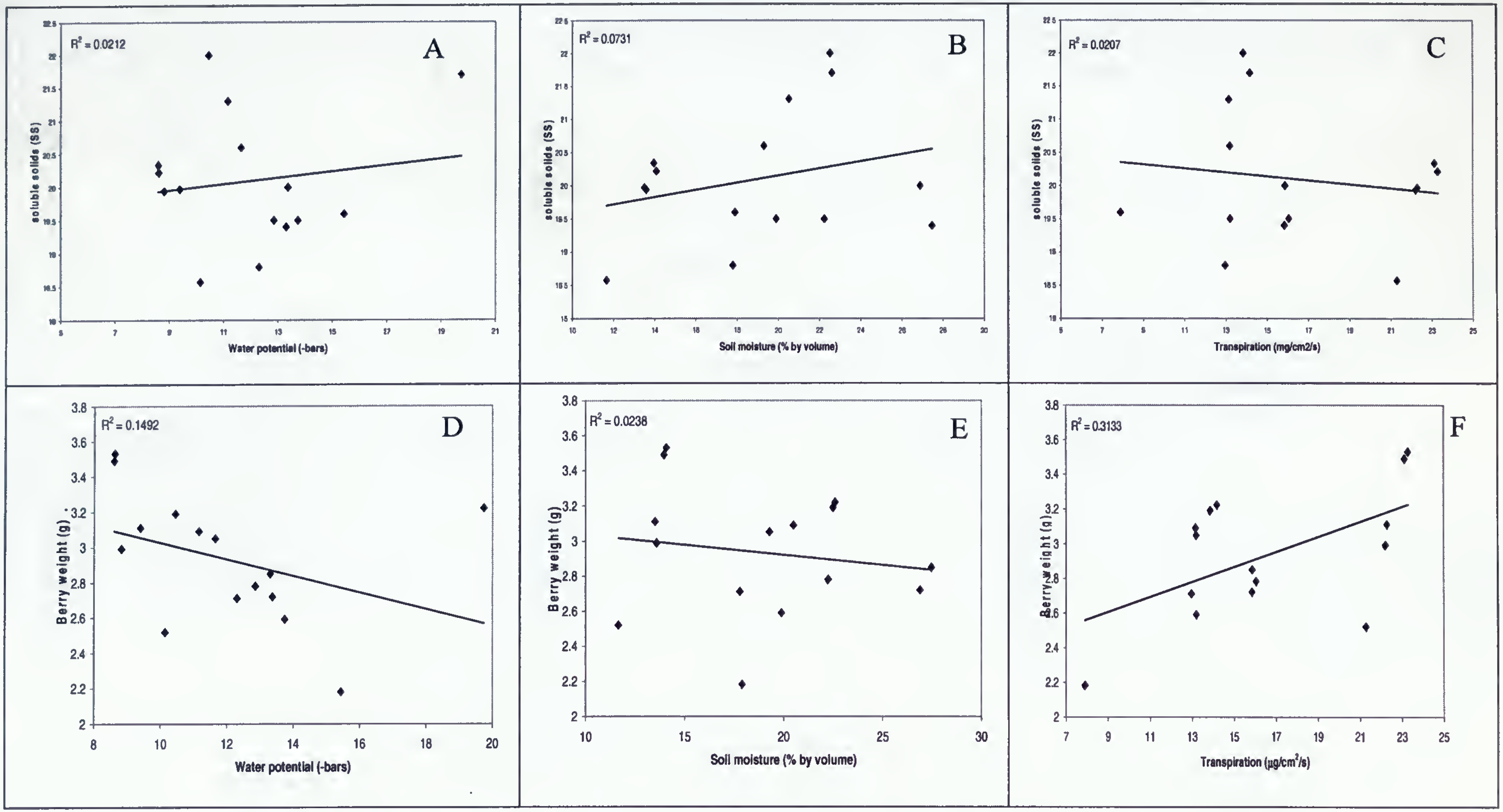

Figure 27: Relationships between vine water status and berry composition variables, Hipple Vineyards, Beamsville, ON, 2003-2005

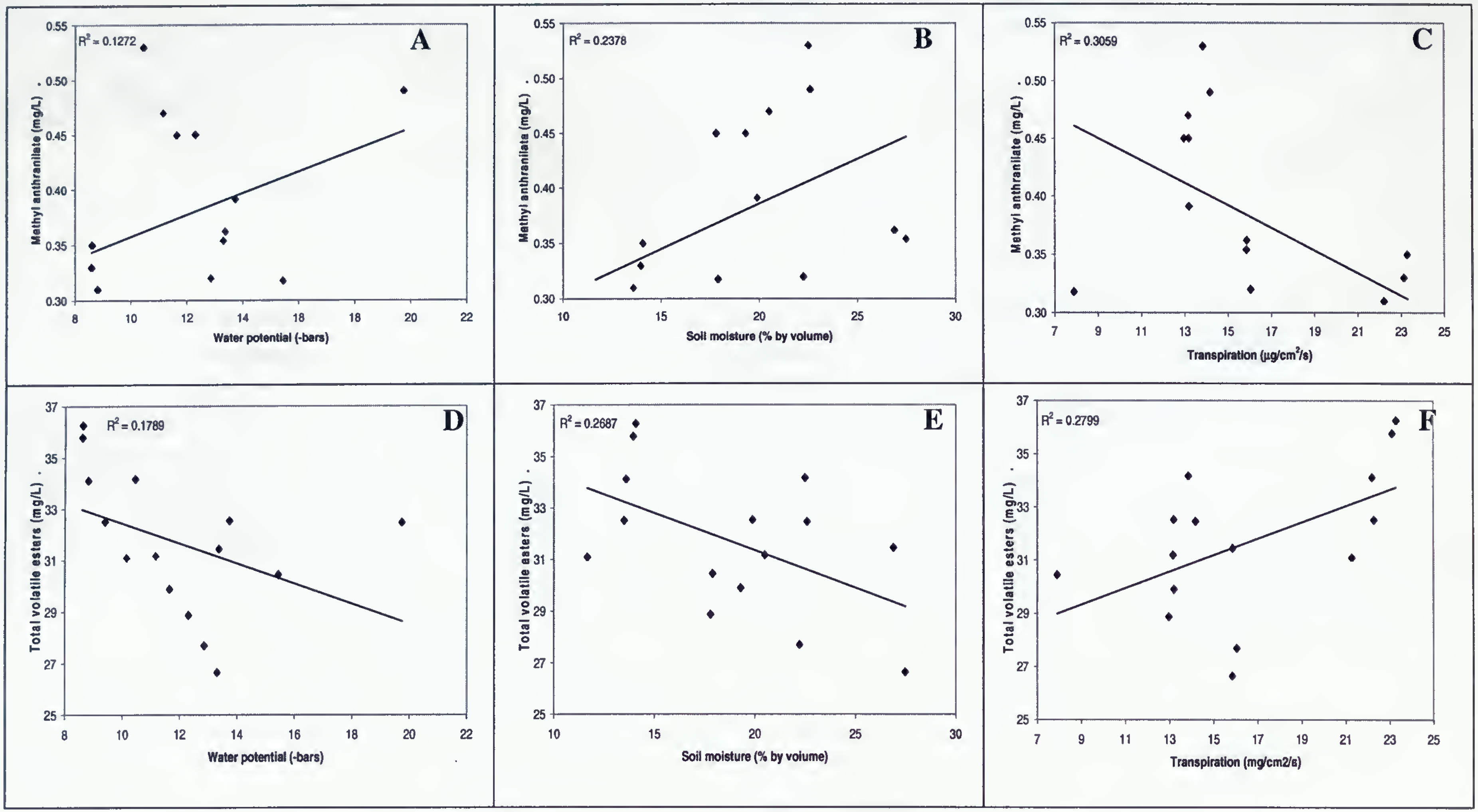

Figure 28: Relationships between vine water status and berry composition variables, Hipple Vineyards, Beamsville, ON, 2003-05.

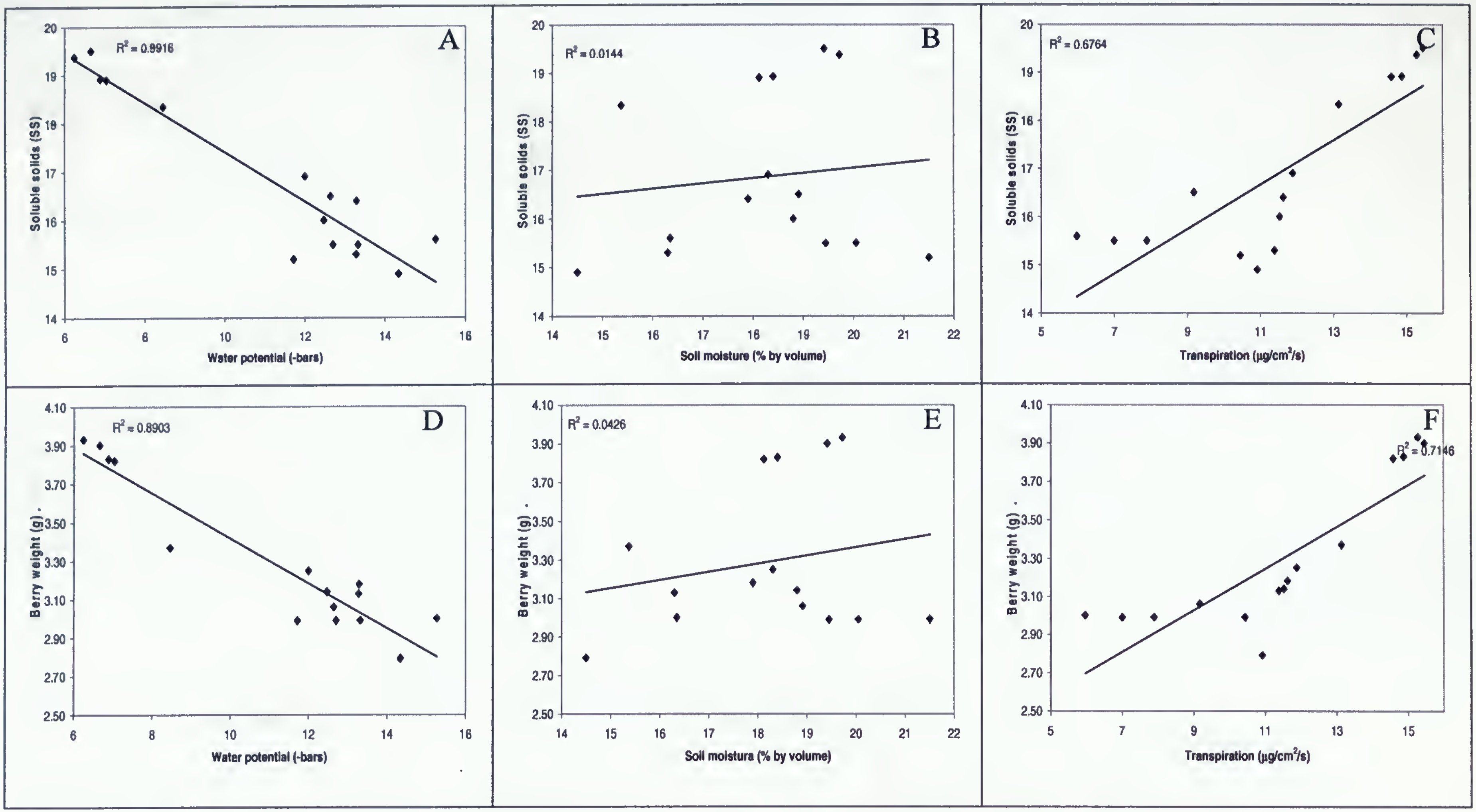

Figure 29: Relationships between vine water status and berry composition variables, Lambert Vineyards, Niagara-on-the-Lake, ON, 2003-05.

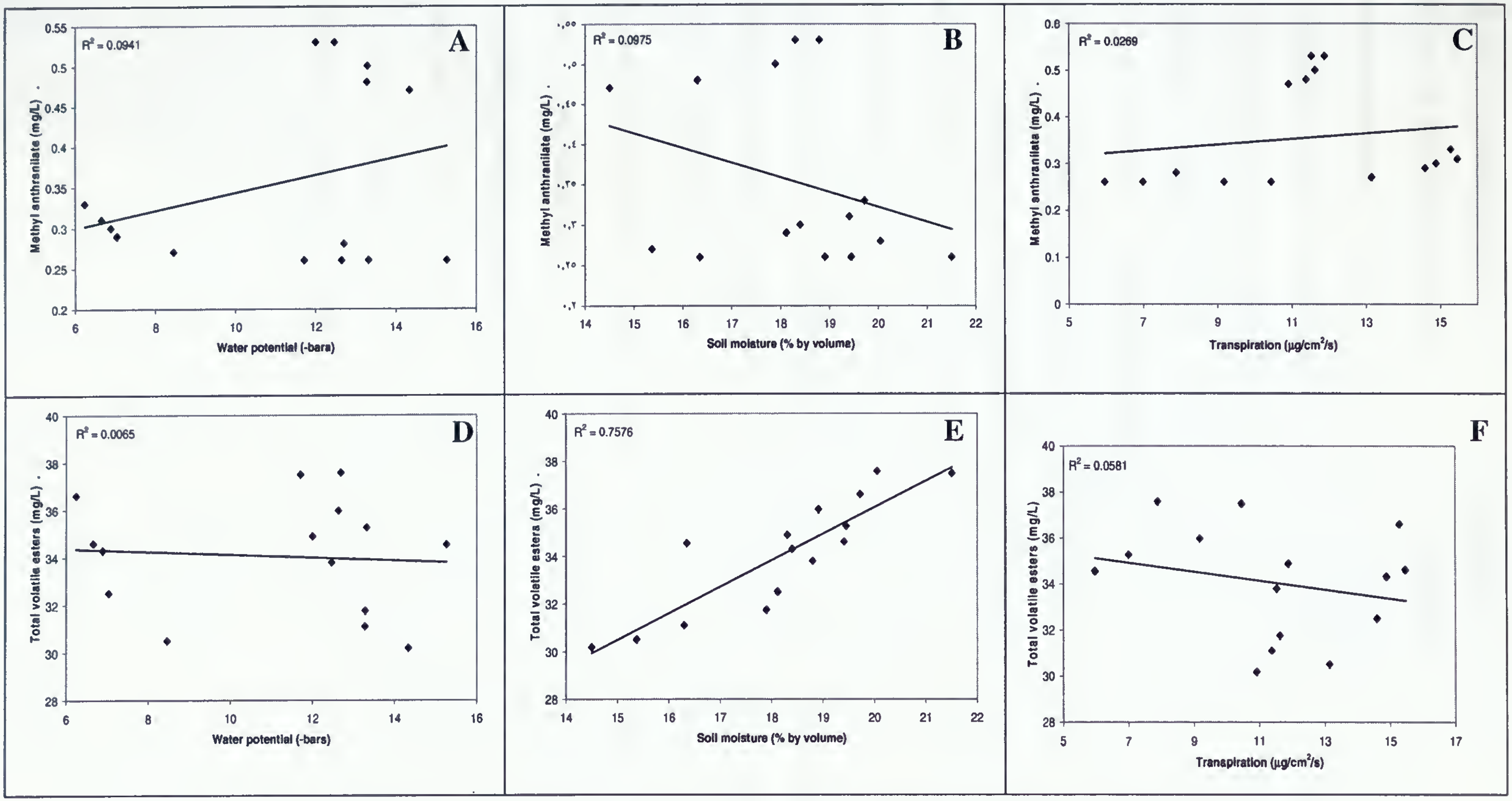

Figure 30: Relationships between vine water status and berry composition variables, Lambert Vineyards, Niagara-on-the-Lake, ON, 2003-05.

Relationships between water status and fruit composition variables. Some cursory analysis was attempted to elucidate possible relationships between soil and vine water status and key berry composition variables. Possible correlations amongst three water status variables (transpiration, leaf water potential, and soil moisture) and four berry composition variables (berry weight, Brix, MA and TVE) were explored for each of the two sites. At the Hipple site, relationships involving Brix (Figure 27A to C) were weak. A relatively strong correlation (R^2 = 0.31; Figure 27F) existed between transpiration and berry weight, while although weak (R^2 = 0.15), the inverse leaf ψ vs. berry weight relationship (Figure 27E) appeared noteworthy. Soil moisture and MA were weakly correlated (R^2 = 0.24; Figure 28B), while transpiration was weakly and inversely correlated with MA (R^2 = 0.31; Figure 28C). TVE followed opposite trends to MA in its relationships with soil moisture and transpiration.

Data from the Lambert site underscores the site-specific nature of the water status vs. berry composition relationships. Soluble solids (SS) was inversely correlated with absolute value of ψ (R^2 = 0.89; Figure 29A), suggesting strongly that low vine water status was actually increasing Brix. However, a positive relationship between transpiration and soluble solids (SS) (R^2 = 0.68; Figure 29C) suggested otherwise. Leaf ψ also displayed an inverse correlation with berry weight (R^2 = 0.89; Figure 29D), again suggesting strongly that low vine water status increased berry weight, whereas transpiration and berry weight were positively correlated (R^2 = 0.71; Figure 29F). MA and water status variables were not correlated (Figure 30A to C). However, an apparent strong relationship existed between soil moisture and TVE (R^2 = 0.76; Figure 30E).

Discussion

Two hypotheses were put forth at the initiation of this study. It is worthwhile re-stating these here: 1. I hypothesized that supplemental irrigation of Sovereign Coronation table grapes using the Penman-Monteith scheduling would enhance vine performance, berry composition, and yield through alleviation of water stress; 2. I further hypothesized that water budgets calculated from this equation would be validated by measurements of transpiration, water potential, and soil moisture. These hypotheses will be discussed in the context of the data.

H1. Supplemental irrigation of Sovereign Coronation table grapes using the Penman-Monteith scheduling would enhance vine performance and berry composition through alleviation of water stress.

Irrigation should alleviate water stress, if present. Therefore, this hypothesis carried with it the assumption that some or all irrigation treatments would increase overall yield each year. Presumably, this yield increase would be due to increases in cluster weight, berry weight, or both. It was assumed that provision of water through irrigation would enhance vegetative growth, which would be measurable in terms of increased vine size. Alleviation of water stress also might have increased photosynthetic rate and carbohydrate translocation, which would have been reflected in soluble solids (Brix) measurements in the fruit. It is also possible that if fruit maturity were accelerated by irrigation that other components of fruit composition could have been modified positively—TA would have theoretically decreased relative to non-irrigated treatments while pH and concentrations of secondary metabolites would have increased, particularly those groups of compounds that were glycosylated.

5.1. Yield components.

In general, this hypothesis was at best only partially proven by the data. No yield increases were observed in 2 of 3 years (2003 and 2004) at both sites. However, it is noteworthy that in the driest season (2005), yields were increased over the control in all irrigated treatments at the

Lambert site, and in three of four irrigated treatments at the Hipple site. The magnitude of these increases was+ .11 to 36 %. This would of course represent a substantial payment increase to the grower. Similarly, no increases were observed in clusters per vine in 2003 and 2004 that could be attributable to irrigation, but two of four irrigated treatments at Lambert and all four at Hipple exceeded the control, and these increases (up to 28%) were likely contributors to overall yield. Cluster weights also increased slightly in irrigated treatments over the control; in 2003, for instance, three irrigated treatments exceeded the control by as much as 22% at Lambert and two at Hipple exceeded the control by up to 25%, and one exceeded the control at Hipple in 2005. Berries per cluster showed virtually no response worthy of mention. Of greatest importance were the increases in berry weight associated with irrigation. All treatments exceeded the controls at Lambert in two of three seasons, and most irrigated treatments had higher berry weights than the controls at Hipple in all three seasons. Studies on many cultivars locally have proven that irrigation improves yield and berry weight significantly over non-irrigated treatments (Cline et al. 1977, Lowrey 2004, Tomek 2003).

5.2. Vine size

This hypothesis was adequately proven by the available data. Irrigation enhanced vegetative growth. Weight of cane pruning was higher than the control in all irrigated treatments in the 2003 growing season at both sites. The increase in irrigated treatments was as high as 74% greater than the non-irrigated treatment (Figures 17 and 18). These increases occurred despite a lack of response in most yield components during those seasons, and it was therefore clear that supplying the vines with supplemental water resulted in longer and more vigorous shoots. It was nonetheless clear that the response of the vines to irrigation with respect to vine size generally satisfied the hypothesis. A benefit of lower vine size in control treatments might be the reduction in pruning costs for the grower, as well as the possibility of reduced canopy shade (Smart et al. 1985).

5.3. Berry weight and composition.

The hypothesis that irrigation would improve berry weight and composition was only partially proven by the data, primarily berry weight and soluble solids. Irrigation increased berry weight by nearly 15 to 20% in most irrigated treatments in both sites compared to the untreated controls. The exception was the Lambert site in 2003. This is in agreement with other research that has shown that increased irrigation results in higher berry weights (Christensen 1975, Lowrey 2004, Smart 1985, Tomek 2003, Williams and Matthews 1990). Berry weight consistently appeared to be the main factor leading to the increased yields, when present, in irrigated treatments (Tables 2 and 3).

In general, soluble solids were higher in irrigated treatments than in non-irrigated treatments over the 3 years. In 2003, only one irrigated treatment at each site exceeded the control. However, in 2004 and 2005, three of four and four of four irrigated treatments, respectively, exceeded the control at the Lambert site. At the Hipple site, all four irrigated treatments exceeded the control in 2004 and 2005; the ET150/0.5-0.8 treatment attained 22 Brix in 2004 (14 % more than the control), which was the highest value across both sites for the 3 years (Figure 22). It is normally assumed that larger berries will automatically have lower sugar concentrations than smaller berries due to an increase in water to soluble solids ratio. However, results from our experiment and previous studies (Balo et al. 2002, Ginestar et al. 1998, Goodwin and Jerie 1989, Lowrey 2004) showed that this is clearly not the case all the time. That might be explained by the fact that water-stressed non-irrigated treatments experienced reduced transpiration rates, and therefore gas exchange in general was compromised, including photosynthesis, the source of sucrose. This reduction in photosynthesis could explain the lower soluble solids in many of the low- or non-irrigated treatments.

The TA values for the irrigated treatments were generally higher than the control in 2003 in the Lambert site but were decreased by irrigation in 2004 and 2005 at both sites. The enhanced

vegetative growth likely led to increased shade in 2003, hence the higher TA values in irrigated treatments that season. The explanation for the 2004 and 2005 results might be that water diluted some of the acids (Mullins et al. 1992); also, water stress can delay fruit maturity without degradation of grape acids (Lowrey 2004, McCarthy 1990, Mullins et al. 1992, Reynolds and Naylor 1994). Similar results have been found locally in other cultivars (Lowrey 2004, Tomek 2003). Treatment differences in berry pH were statistically significant but not necessarily agriculturally significant. Berry pH increased in irrigated treatments at both sites in 2005 but decreased slightly with irrigation at the Hipple site in 2003 and 2004 and at the Lambert site in 2004. The grape berry is a highly buffered system, and it appears that irrigation does not have a large effect on pH, which agrees with other findings (Ligetvari 1986, Lowrey 2004, Tomek 2003). It may be possible that with increased cluster exposure in non-irrigated vines, because of reduced vigor due to reduced water available to the vines that the pH may have been reduced (Mullins 1992). This is consistent with the data from the 2005 growing season where the pH was lowest in the control treatments.

Hue, which measures ratio of yellow/brown color to that of red/blue color, increased in most irrigated treatments in both sites in all three seasons of study (Tables 6 and 7). The 2003 results showed the highest magnitude of influence of irrigation. The hue values in the grapes from the Lambert site tended to be slightly higher than Hipple vines. The explanation of this could be due to the soil type, as the Hipple soil was heavy clay and this affected the amount of water available to the vines. Color intensity values were reduced in irrigated treatments in 2003, while there was an increasing trend in irrigated treatments over the non-irrigated treatment in 2004 (Hipple only) and 2005 (both sites). This is could be due to the very dry conditions and higher temperatures during that season. These findings agreed to some degree with studies on Tempranillo, in which an increase was found in hue and color intensity in irrigated vines (Esteban et. al. 2001); they also noted that the intensity value depended on seasonal conditions.

Similar to hue and intensity data, total anthocyanins decreased in irrigated treatments in 2003 (both sites) and in 2004 (Lambert site only), but increased in irrigated treatments in the 2005 season at both sites and in 2004 at the Hipple site. In the 2003 season the control treatments had the highest anthocyanin concentration at both sites (Tables 6 and 7). The 2005 data were consistent with other studies that concluded that water increased anthocyanin development in red grape cultivars (Bravdo et al. 1985, Esteban et al. 2001). Some studies also agreed with our 2003 results, that the anthocyanins in the skins of berries from irrigated vines that were high-yielding was lower than in the skins of berries from low-yielding non-irrigated vines (Esteban et al. 2001, Freeman et al. 1983, Mullins et al. 1992).

Total phenols were lowest in the irrigated treatments in the 2005 season at both sites, but in the 2003 and 2004 growing seasons the phenols were higher in irrigated treatments compared to non-irrigated controls in both sites (Tables 6 and 7). This might have been related to the hot dry weather in 2005 season in which non-irrigation led to small canopy size and more cluster sunlight exposure; in the 2003 and 2004 seasons, where conditions were cooler, the non-irrigated vines had lower phenols than many irrigated treatments, perhaps due to higher vegetative growth and more fruit shade. Smart et a1. (1985) indicated that higher canopy density resulted in clusters that were less exposed to direct solar radiation, a more shaded condition in the cluster zone, and lower berry temperatures, ultimately leading to juices with a lower concentration of anthocyanins. Total phenol concentrations in the juice of grapes from Hipple vines were substantially higher than Lambert vines in the three seasons; this could be due to soil differences between two sites.

Methyl anthranilate (MA) concentrations were highest in the irrigated treatments in all three growing seasons at both sites (Figure 23 and 24). A study on Concord and Niagara showed that the lowest MA concentrations were found in berries of non-irrigated treatments (Reynolds et al. 2005). The MA in 2004 was higher than in the 2003 and 2005 growing seasons in both sites,

and the 150ET treatments in 2004 had the highest MA concentrations across all treatments and seasons. These results are contrary to other studies where water stress increased the accumulation of flavor compounds (McCarthy and Coombe 1988). However, in the wet 2004 season, the berries accumulated relatively high MA concentrations. However, other studies have shown that dry or low nitrogen conditions encourage MA accumulation in fruit (Hoenicke et al. 2001). Total volatile esters (TVE) also were higher in most irrigated treatments over the three seasons at the Lambert site (Figure 25). This trend was also found in the Hipple site in 2004 and 2005 where the irrigated treatments had the highest TVE values relative to the controls. This could be due to the same reasons mentioned regarding MA concentration. The treatments with the highest yields and berry weight produced higher concentrations of TVE compared to other treatments. This again suggests that a treatment with lower water stress accumulates TVE at high concentrations.

5.4 Relationships between vine water status and berry composition

Although exploratory at best, the relationships between soil and vine water status measurements and specific berry composition variables are worthy of mention. It was particularly interesting that some relationships such as those between vine water status and soluble solids were present at one vineyard (Lambert) and not the other; this may have been due to the much larger canopy volume at the Lambert site, which would have been more susceptible to low soil water status. It was also worthy of note that low vine water status, as measured by leaf ψ, was associated with higher soluble solids at the Lambert site, but this may have been due to lower berry weights and berry size and the attendant concentration effect. Increased soluble solids was clearly associated with increases in transpiration rate at that site also, while berry weight and transpiration were positively correlated at both sites.

Of particular interest were the relationships between MA and TVE vs. soil moisture and transpiration at the Hipple site. Essentially, these were inexplicably mirror images of each other;

MA was positively correlated with soil moisture and inversely with transpiration, while TVE showed opposite trends in relation to these variables. Increased MA concentration has been linked in some circumstances to low soil and vine water status (Hoenicke et al. 2001), hence these relationships with soil moisture in Sovereign Coronation are contradictory to some previous literature; however, one study with Concord and Niagara tends to corroborate our data (Reynolds et al. 2005). Conversely, the inverse relationship between MA and transpiration is supportive of the hypothesis that MA production is somehow triggered by drought stress. TVE, on the other hand, appeared to be diminished by increasing soil moisture, but increased by transpiration. This observation is more in accordance with Reynolds et al (2006), who observed that early and mid-season moisture stress reduced concentration of monoterpene flavorants in Gewurztraminer berries.

H2. Water budgets calculated from this equation would be validated by measurements of transpiration, water potential, and soil moisture.

This hypothesis carries with it the simple assumption that use of irrigation scheduling would improve soil and plant water relations. Specifically, calculation of an ET_c value based upon either 100% or 150% replacement of ET_0, coupled with a K_c based on canopy volume, should theoretically optimize vine water relations. Measurement of soil water, transpiration, and leaf ψ should therefore confirm that the addition of water improved vine water status.

5.5. The usefulness of irrigation scheduling.

According to the weather data (Figures 9 and 10), the mean monthly ET_0 for the Niagara region generated by the Penman-Monteith equation was highest in the 2005 growing season, and lowest in 2004. The general trend in ET_0 appeared to be a smooth rise from mid-June to a peak in mid-July and early August, followed a smooth decline for the remainder of the growing season. ET_0 rates peaked substantially between late June and mid–July/ early August 2005 when

temperatures were approaching their annual high and solar radiation were at its maximum. This was particularly noticeable because of the very dry weather and high solar radiation in the 2005 growing season. Low ET_0 values in 2004 were due to several rain events that resulted in cloudy, humid and cool conditions. Seasonal ET_0 values using the Penman-Monteith equation for Niagara were 852mm (2003), 659 mm (2004), and 1241mm (2005), respectively. These values are very similar to irrigation requirements suggested for San Joaquin in California, which vary between 650 and 1650 mm/season (State of California 1986).

Use of weather data from Ontario weather network (OWN) from the previous week along with two different K_c values of 0.75 and 0.2 to 0.8 (based on canopy volume) was only partially verified to be adequate in relieving vines from water stress. Irrigated treatments at some instances in the growing season displayed either soil moisture values below wilting point and/or leaf ψ values < 12 bars. Therefore, soil and plant water relations data only partly support the hypothesis that the Penman-Monteith equation could be used in Niagara to measure and ultimately fulfill vine water needs. Irrigation was definitely needed in the summers of 2005 and 2003 as it was in previous dry seasons such as 2001 and 2002 (Reynolds et al. 2005), but irrigation was also beneficial in 2004 regardless of rain events. However, there were points during the growing season when the ET_c calculated by the Penman-Monteith was inadequate in supplying vine water needs.

The practice of using the previous week's ET to calculate the amount of water to apply during the upcoming week's irrigation generally worked adequately in dry years such as 2003 and 2005. A potential disadvantage to this method, however, occurs if a large amount of precipitation is received between irrigations, reducing the ET_0 and consequently the water volume required for the upcoming week.

As the season progressed, vine canopy size increased, and therefore so did the plant water requirements (McCarthy 2001, Schultz and Matthews 1988, Williams and Matthews 1990). This

was addressed in the irrigation scheduling by the use of a K_c that increased with increasing canopy volume. In midsummer when temperatures were high and relative humidity low, the evaporative demand by the plants increased as result of these the climatic conditions (Williams and Matthews 1990).

5.6. Vine and soil water status

5.6.1. Soil moisture

The hypothesis that use of irrigation based upon calculated ET values would improve soil water status was only partially proven by our data. All treatments were very low in soil moisture in the 2005 growing season (Figures 11C and 12C), and these values were frequently below the published wilting point for Toledo clay of 18.7 % (Kingston and Presant 1989). A reason for the low measured soil moisture values could be due in part to the combination of using a short-pronged Theta probe (< 100 mm) to measure soil moisture. An additional possibility for the low soil moisture values might be that the Penman-Monteith equation may have simply under-estimated the amount of water needed by these vines growing on this particular soil. These values are similar in magnitude to the 14.8 % soil moisture value measured in a drought-stressed Concord vineyard in Honeoye gravelly sandy loam soil in NY State (Poni et al. 1994); however, that soil type has a much lower wilting point than Toledo clay. Clay soils are in general poorly drained and thus if they become dry they are difficult to re-wet. As a result, even when the exact amount of water was added, it may not have been absorbed by the vine.

The soil moisture levels declined throughout the growing seasons. Higher moisture levels were consistently measured for irrigated treatments compared to non-irrigated vines in all 3 years of the study (Figures 11 and 12). These results also offer some proof that the drip irrigated treatment rows did not add moisture in the soil around vines in nearby non-irrigated rows. However, all treatments at the Lambert site in 2004, including the non-irrigated control, had soil moisture values that fell between wilting point and field capacity in both sites; this was possibly

due to the rainfall in that year. Control vines at the Hipple site were below wilting point throughout the 2004 season. Irrigation certainly supplied the vines with more than adequate water to maintain soil moisture levels consistently above the wilting point and at or below field capacity for the soils in question (Kingston and Presant 1989). High rainfall events in the 2004 growing season caused soil moisture levels for all the treatments at the Lambert site to increase within the available moisture range for plants (between field capacity and wilting point). The rain events also decreased the magnitude of difference between the irrigated and non-irrigated treatments in that year. However, as expected, it was still clear that irrigated treatments had higher soil moisture than non-irrigated treatments.

The 2003 and 2005 seasons were less supportive of our hypothesis. On the positive side, non-irrigated controls had lower soil moisture levels than irrigated treatments at both sites. However, during the peak ET periods, irrigated treatments had soil moisture values below wilting point (Figures 11, 12). These data suggest that calculation of ET values using the Penman-Monteith equation may provide an inadequate estimate of vine water needs. An important point bears repeating: the < 100 mm-long Theta Probe may have under-estimated soil water, and irrigated treatments may have indeed had higher soil moisture values at lower depths.

Our data suggests therefore that Penman-Monteith-based scheduling of irrigation may increase soil moisture levels above wilting point in some seasons, thus providing the vine with adequate water for its physiological needs. However, this still requires more verification with better instrumentation.

5.2.2. Water potential

Leaf water potential (ψ) is important for all plants; it drives water uptake from the soil and throughout the intact plant (Taiz et al. 2002). Water potential is affected by the environmental conditions around the plant; if conditions become excessively stressful for the plant, it limits the amount of water loss from the leaves via the stomata (Winkel and Rambal 1990). Overall,

differences between treatments for leaf ψ occurred almost every week throughout the three growing seasons, and the data followed a trend whereby ψ became more negative throughout the season for treatments that were not irrigated. Studies have found that when white grape cultivars begin to experience water stress, leaf ψ fall to < -10 bars (Smart 2000). When water stress continues, the leaf ψ decreases further to < -12 bars, which causes full stomatal closure (Smart 1985).

The hypothesis suggested that leaf ψ would be increased by irrigation, and that non-irrigated vines would experience periods when leaf ψ would decrease to < -12 bars. This theoretical scenario was only partially true. Non-irrigated treatments indeed had ψ values that were usually lower than their irrigated counterparts, and under most cases, these values were < -12 bars. However, on some occasions irrigated treatments also had ψ values < -12 bars, suggesting that the volume of irrigation water applied was inadequate. This was particularly the case at the Lambert site in 2003 and 2005, and it was observed at the Hipple site in all three seasons. It appeared that ψ dropped to < -13 bars for all treatments in some weeks, which suggested that water stress was present for the vines in both irrigated and non-irrigated treatments (Lambert 2003 and 2005, Hipple all seasons; Figures 13 and 14). This was due to increased evaporative demand that resulted from a larger canopy and less water applied to the vines (Lowrey 2004, Smart 1974, Williams and Matthews 1990). Highly negative ψ (< -12) were also generated near the end of the growing season in 2004 at the Lambert site (Figure 13B). In 2005, mean ψ was as low as -14 bars but only in non-irrigated treatments (Figures 13C and 14C). In most cases that season, water stress was clearly present (e.g. slightly wilted leaves that were warm to the touch) in all non-irrigated treatments and not present in those treatments that were irrigated.

These results again confirmed that irrigation was required for the dry summers experienced in 2003 and 2005. However, they only partially supported the hypothesis that irrigation

scheduling determined by the Penman-Monteith equation was successful in providing vines with the adequate volumes to fulfill the vineyard's water needs. Irrigated treatments indeed had higher ψ values (i.e. less negative) than non-irrigated treatments, but sometimes the irrigated treatments still had ψ values < -12 bars, suggesting that they were still possibly experiencing water stress. However, from an entirely observational standpoint, irrigated vines showed no signs of water stress, while non-irrigated vines clearly were under water stress at certain times of the season. Some researchers have suggested that taking stem ψ is more favorable for indicating vine water status. It is believed that stem ψ distinguishes between treatments better than the leaf ψ because of the inconsistency those results between bagged leaves on different shoots of the same vine (Choné et al. 2001). To avoid any uncertainty associated with leaf ψ, stem ψ could be used in future assessments of vine water status.

5.2.3. Transpiration

Our hypothesis suggested that like soil moisture and leaf ψ, transpiration would likewise increase in response to supplemental irrigation. This was generally true, but in the absence of any benchmark values for vine transpiration (analogous to wilting point for soil moisture or the -12 bar value for ψ), the existence of water stress cannot be assessed by transpiration values. Transpiration rates were nonetheless highest across all seasons and sites for irrigated treatments. Transpiration rates for all treatments were higher in 2004 compared to 2003 and 2005; this was due partially to high rainfall in 2004 (Figures 15 and 16). Viewed across all seasons and sites, the irrigated treatments showed the consistently-highest transpiration rates (7 to 18 $\mu g/cm^2/s$) on almost all sampling dates, whereas control treatments transpired lowest (4 to 10 $\mu g/cm^2/s$), which suggests that water stress may have been present in non-irrigated vines. The difference in transpiration rate trends among the vineyards over the three seasons was mainly a function of the weather patterns over the latter part of the growing season. In 2003 and 2005, vines experienced

a drought so severe that even the supplemental irrigation could not raise transpiration levels. The 2004 season provided less potential for drought stress, due to adequate and timely precipitation, and transpiration rates across treatments were relatively similar.

In dry years such as 2003 and 2005, vines under water stress may shut down their gas exchange systems at certain points. Non-irrigated treatments clearly had substantially lower transpiration rates and thus potentially endured more water stress. These findings concur with other studies (Choné et al. 2001, Fuller 1997, Gomez-del-Campo et. al. 2002, Lowrey 2004, Rodrigues et al. 1993, Tomek 2003, Winkel and Rambal 1990) and support the notion that the Penman-Monteith equation might alleviate water stress by providing accurate values for vine water requirements.

Conclusions

This study has provided insight into irrigation and its magnitude of impact in cool climate regions such as Niagara, where vineyards in this region have typically not been irrigated because of a lack of a perceived cost benefit. This study provides inefficiency data and calculation tools to the growers for making the right decisions on when, how and how much to irrigate their crops. Additional research will concurrently expand the understanding base and modify the techniques for appropriate vineyard irrigation in Niagara.

This study shows some validity for the use of the Penman-Monteith equation for assessing water needs in Niagara. The Penman-Monteith equation calculated ET_0, and, multiplied by a K_c value to account for canopy development, provided a relatively easy to use measure of ET_c. The actual utility of using weather data from Ontario weather network (OWN) from the previous week to calculate ET_0 along with different K_c values (fixed or based on canopy volume) was only partially adequate in providing irrigation values that would relieve or prevent water stress in grapevines. Irrigated treatments in some cases during the growing season displayed either soil moisture values below wilting point and/or leaf ψ values < 12 bars. Therefore, soil and plant water relations data only partly supported the hypothesis that the Penman-Monteith equation could be used in Niagara to anticipate vine water needs.

Irrigation was certainly required in the dry summers of 2005 and 2003 as it was in previous dry seasons such as 2001 and 2002 (Reynolds et al. 2005). It appeared from some of our data that irrigation was also of some benefit in 2004 despite rain events. The Van der Gulik equation (Van der Gulik and Eng, 1987) theoretically could have overestimated irrigation needs by using a fixed K_c of 0.75, especially early in the season when the canopies were small. However, as canopy development was complete, and no further rain events were recorded, it was likely that the crop coefficient used by the Van der Gulik equation was in fact inadequate. Soil moisture,

leaf ψ, and transpiration measurements suggested that irrigated treatments consistently had superior soil and vine water status compared to non-irrigated treatments, but frequently even irrigated vines displayed water relations data that suggested that they were still under water stress.

Irrigation led to increased berry weight and higher vine size. The increased berry weight was the basis for the slight increased yield in 2005 growing season. In addition, the larger berries did not result in lower Brix for the irrigated treatments. Berry pH increased in irrigated treatments one season, and TA values for the irrigated treatments were generally lower than non-irrigated treatments in 2004 and 2005 at both sites, but TA values for the irrigated treatments were higher than the control in 2003 in the Lambert site. Among secondary metabolites, anthocyanins and phenols followed a trend whereby irrigated treatments had the lowest phenols in the hot dry seasons at both sites, but in the wet growing season the total phenols were higher in irrigated treatments compared to non-irrigated controls in both sites. Methyl anthranilate concentrations were very sensitive to drought stress. Adding water to the vines increased MA, suggesting that lower stress and larger berries led to higher MA accumulation. TVE also increased in irrigated treatments.

Water status data for non-irrigated treatments on some sampling dates did not meet the official parameters for being classified as water-stressed vines, but they were still much lower than the irrigated treatments. The precipitation supplied to the vines in non-irrigated treatments led to early vine growth that could not be compensated for by the plant as it encountered a summer of drought such as 2005. Eventually, these vines suffered water stress and consequently yielded less, had lower Brix, and had lower cane weights. This agreed with research that showed mild water stress to be detrimental in terms of berry weight, soluble solids, pH, and TA (Ginestar et al. 1998, Lowrey 2004, Mullins et al. 1992, Reynolds and Naylor 1994, Rühl and Alleweldt 1985, Smart 1985, Tomek 2003).

Soil type, method of irrigation, severity of drought stress, and amount of water added all likely played contributing roles in the efficacy of the irrigation. Low soil moisture values suggest that no matter how much water was added, the Toledo clay soil was not adequately re-wetted. More studies incorporating data from wetter seasons may be advantageous in modifying the formula and determining the best K_c value to use. In particular, these results suggest that irrigation of Sovereign Coronation is worthwhile, and that growers would benefit from the increased berry weight, higher soluble solids and low TA values. However, it must also be said the the Penman-Monteith equation in combination with the Van der Gulik equation appeared to underestimate irrigation needs in Niagara during dry seasons.

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