Research Reports

Irrigation Scheduling for 'Sovereign Coronation' Table Grapes Based on Evapotranspiration Calculations and Crop Coefficients

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SUMMARY. Several irrigation treatments were evaluated on 'Sovereign Coronation' (*Vitis labruscana*) table grapes at two vineyard sites in Ontario, Canada in 2003 to 2005 to assess the usefulness of the Food and Agriculture Organization of the United Nations Penman-Monteith equation for predicting vine irrigation needs. Data (relative humidity, wind speed, solar radiation, and temperature) for calculating reference evapotranspiration (ET_o) were downloaded from the Ontario Weather Network. The five irrigation treatments were nonirrigated control plus four based on combinations of one of two ET_o values [100% (ET_{100}) or 150% (ET_{150})] and two crop coefficients [K_c (fixed at 0.75 or 0.5–0.8 based upon increasing canopy volume)] used to calculate the required irrigation water volume. Transpiration (T_s), leaf water potential (ψ), and soil moisture data were collected in all three seasons. Yield components data were collected and berries were analyzed for soluble solids, pH, titratable acidity (TA), anthocyanins, methyl anthranilate (MA), and total volatile esters (TVE). Irrigation typically increased T_s rate and soil moisture; the nonirrigated treatment showed consistently lower T_s and soil moisture over the three seasons. Irrigation also increased leaf ψ , which was lower throughout the three seasons for nonirrigated vines. Irrigation additionally increased yield and its various components (clusters per vine, cluster weight, and berries per cluster) in 2005. Berry weights were higher for irrigated treatments at both sites, and were consistently the main variable leading to yield increases. Soluble solids was highest for the $K_c = 0.75$ treatments. pH, TA, anthocyanins, and phenols were highest in nonirrigated treatments in 2003 and 2004, but were highest in irrigated treatments in 2005. MA and TVE were highest in the ET_{150} treatments. The use of irrigation was effective in reducing water stress and for improving yield and fruit composition of 'Sovereign Coronation' table grapes in the Niagara region of Ontario. The ET_{150} treatments were particularly beneficial. Soil and vine water status measurements indicated that irrigation was required for Summer 2003 and 2005 due to dry conditions.

experience low rainfall during the growing season and do not have enough water in their soil profile to supply vine growth (Williams, 2001). Areas such as California, Australia, and Chile use irrigation to supply the necessary water requirements for their vines, and produce very high-quality wine and table grapes (*Vitis vinifera*) that under natural drought conditions would not be possible. Several years of drought in the Niagara region have led to water stress-related problems such as those described elsewhere; these include low yields (Matthews and Anderson, 1988; Smart and Coombe, 1983), poor fruit composition (Reynolds et al., 2007), decreased vine photosynthesis and transpiration (Choné et al., 2001; Fuller, 1997; Gomez-del-Campo et al., 2002), and poor shoot growth (Reynolds and Naylor, 1994). These drought conditions have led many grape growers in the Niagara region to examine the feasibility of irrigation. Numerous studies indicate that irrigation is a vehicle for overcoming water stress-induced problems (Gomez-del-Campo et al., 2002; Williams and Matthews, 1990).

The table grape cultivar Sovereign Coronation ['Patricia' × 'Himrod' (Denby, 1977)] has become widely planted in the Niagara Peninsula, and its acreage has increased substantially in the last few years in Ontario and British Columbia. The Fresh Grape and Tender Fruit Marketing Board in Ontario is concerned about achieving optimal maturity for 'Sovereign Coronation', and irrigation may be an effective way of enhancing fruit maturity, particularly in dry seasons. However, the use of irrigation for *Vitis labruscana*-based juice and table grapes in Ontario and the north-eastern and midwestern United States has received very little attention. In Arkansas, Spayd and Morris (1978) increased yield of 'Concord' (*V. labrusca*) by 2 t·ha⁻¹ by using irrigation. Subsequent studies showed that irrigation could increase yield and soluble solids in 'Concord' during drought seasons (Morris and Cawthon, 1982). In Ontario, Cline et al. (1985) found that irrigation increased yields of Geneva double curtain-trained 'Concord' by 13% as well as increasing berry and pruning weights. In New York, Liu et al. (1978) measured leaf water potential

Niagara Peninsula (Ontario, Canada) vineyards are normally not irrigated because

of a lack of a perceived cost-benefit ratio. The majority of irrigated vineyards worldwide are in areas that

<-16 bars in field-grown 'Concord' vines; however, despite these conditions, leaves did not experience stomatal closure, suggesting that the vines were not water-stressed. 'Niagara' (*V. labruscana*) appears to respond more favorably to supplemental irrigation than 'Concord' (Reynolds et al., 2005a); however, under intensive management that may include minimal pruning, irrigation is considered to be an essential adjunct (Lakso and Pool, 2001).

Growers of 'Sovereign Coronation' have experienced problems with low sugar, high acid, and low color intensity in years with drought conditions. 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 for research on irrigation of table grapes to gain a better understanding of the impact irrigation has on table grape quality. The greatest concern is to know 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 Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith equation (Allen et al., 1998) are used to schedule irrigation needs by calculating reference evapotranspiration from relative humidity, wind speed, solar radiation, and temperature values, which are downloaded from databases such as the Weather Innovations Network in Ontario. ET_o values can then be used with a crop coefficient (normally

based upon canopy volume) to calculate the volume of irrigation water required. Therefore, a major element of this 3-year project consisted of using the FAO Penman-Monteith formula for calculating ET_o for use in irrigation scheduling. Vine performance and berry composition were determined to assess their response to irrigation. A secondary focus was on methyl anthranilate and volatile ester aroma compounds, which are very important odor-impact compounds for this cultivar.

The general objectives of this study were to assess the effectiveness of using the FAO 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. To fulfill these objectives, combinations of 2% ET_o values and two crop coefficients, plus a nonirrigated control, were tested at two sites in the Niagara Peninsula. We hypothesized that supplemental irrigation of 'Sovereign Coronation' table grapes would enhance vine performance, berry composition, and yield through alleviation of water stress. We further hypothesized that water budgets based on the FAO Penman-Monteith equation and other calculations would be validated by measurements of transpiration, mid-day leaf ψ , and soil moisture.

Materials and methods

EXPERIMENTAL DESIGN. Experiments were initiated on 'Sovereign Coronation' vines at Lambert Vineyards in Virgil, ON [lat. 43°13'N, long. 79°08'W (hereinafter referred to as the Virgil site)], and at Hipple Vineyards, Beamsville, ON [lat. 43°09'N, long. 79°25'W (hereinafter referred to as the Beamsville site)] in May 2003. Vines at Virgil Vineyard were 12 years old at the initiation of the trials. Training was four-arm Kniffin, whereby vines were pruned to four 10-node canes plus four two-node renewal spurs. Vines were spaced at 1.5 × 2.7 m (vine × row), fertilized annually with 25 t·ha⁻¹ fresh dairy manure, with floor management consisting of clean cultivation of every other row and ryegrass (*Lolium perenne*) planted in July in the remaining rows. Pest management was consistent with local recommendations [Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), 2002]. Soil at the Virgil site was a composite of two phases of the imperfectly drained Chingua-cousy clay loam soil series [gleyed brunisolic grey brown luvisol ≈ Udalfs, Glossudalf or Hapludalf in the U.S. system of soil classification (Agriculture and Agri-Food Canada, 1998)]; loamy red phase and red phase (Kingston and Presant, 1989). The wilting point reported for the Ap horizon was 13.3% moisture, and field capacity was 27.3% moisture (Kingston and Presant, 1989).

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
10	%	g·L ⁻¹	0.1
0.4047	acre(s)	ha	2.4711
102.7902	acre-inch(es)	m ³	0.0097
0.1	bar	MPa	10
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
0.0283	ft ³	m ³	35.3147
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.04500	kilocalorie(s)/ft ²	MJ·m ⁻²	22.2044
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
1	micron	μm	1
28.3495	oz	g	0.0353
4.3942 × 10 ⁶	oz./inch ²	μg·cm ⁻²	2.2757 × 10 ⁻⁷
1	ppm	mg·L ⁻¹	1
6.8948	psi	kPa	0.1450
2.2417	ton/acre	t·ha ⁻¹	0.4461
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

The Beamsville site contained vines that were 8 years old at the initiation of the trials. Vines were spaced at 1.5×2.7 m (vine $\times$ row), trained to a four-arm Kniffin system, fertilized with $150 \text{ kg} \cdot \text{ha}^{-1}$ of 34N-0P-0K (ammonium nitrate) in spring and $300 \text{ kg} \cdot \text{ha}^{-1}$ of 0N-0P-49.8K [muriate of potash (KCl)] every other year in the fall, with floor management identical to the Virgil site. Pest management consisted of a standard spray program (OMAFRA, 2002). Soil at the Beamsville site was heavy Morley series clay (orthic humic gleysol $\approx$ Aquolls, Humaquepts in the U.S. system of soil classification) whose moisture retention characteristics are not described; however, a similar soil series (Lincoln) has a reported wilting point of 25.0% moisture and a field capacity of 42.3% moisture (Kingston and Presant, 1989).

The five irrigation treatments applied to each of the two sites were: nonirrigated control; $100\% \text{ ET}_o \times K_c = 0.75$; $150\% \text{ ET}_o \times K_c = 0.75$ ($\text{ET}_o \times 1.12$); $100\% \text{ ET}_o \times K_c = 0.5$ to 0.8; and $150\% \text{ ET}_o \times K_c = 0.5$ to 0.8. (Table 1). The irrigated treatments will hereinafter be abbreviated to 100ET/0.75, 100ET/0.5–0.8, 150ET/0.75, and 150ET/0.5–0.8. Irrigation treatments commenced each season around bloom (mid-June) to accommodate the variable K_c treatments (K_c values were ≈ 0.5 at this stage of vine development). Typically, soil moisture and precipitation patterns in the region are sufficient enough to render irrigation unnecessary before this point in the growing season. The irrigation systems consisted of gasoline-powered pumps to bring water to all the rows. RAM (Netafim USA, Fresno, CA) drip tubing was placed down the rows close to the base of the vines. Each line of irrigation tubing was individually controlled by a valve that allowed application of water needed to the individual rows at various times through out the season. Emitters were rated at $8 \text{ L} \cdot \text{h}^{-1}$, and dripper spacing was 1.1 m. All water passed through a sand filter. The experimental block at the Virgil site consisted of 25 rows each containing 129 vines leaving the outside row as a buffer. Experimental design was a randomized complete block with five blocks (replicates) and five treatments. Each treatment replicate was an entire vineyard row. Within each

Table 1. Impact of irrigation treatments on yield components of 'Sovereign Coronation' table grapes at Virgil and Beamsville, ON, Canada in 2003 to 2005. Treatments were not irrigated (control); 100% reference evapotranspiration [ET_o (100ET)] with a fixed crop coefficient ($K_c = 0.75$) or a variable one ($K_c = 0.5\text{--}0.8$); 150% ET_o (150ET) with a fixed or variable K_c value. Boldfaced data indicate those values significantly different from the nonirrigated control, Dunnett's t test; those boldfaced and underlined are significantly less than the control.

Treatment	Virgil, ON						Beamsville, ON					
	Yield (kg/vine) ^z			Clusters (no./vine)			Yield (kg/vine)			Clusters (no./vine)		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Control	8.1	11.4	6.9 d ^y	41	69	40 b	196.9 b	159.7	177.8	66	58 a	45 b
100ET/ $K_c = 0.75$	7.6	12.2	7.7 c	38	72	46 b	203.3 b	162.1	170.8	69	53 ab	45 b
100ET/ $K_c = 0.5\text{--}0.8$	8.4	12.2	8.5 b	39	70	50 b	240.2 a	171.2	176.1	81	59 a	46 b
150ET/ $K_c = 0.75$	7.6	12.1	9.3 a	36	68	54 a	210.1 ab	187.9	174.6	69	56 a	53 a
150ET/ $K_c = 0.5\text{--}0.8$	8.8	11.9	9.4 a	41	70	53 a	211.6 ab	160.1	175.9	87	42 b	46 b
P value	0.5512	0.3785	<0.0001	0.0642	0.7358	<0.0001	0.0354	0.1944	0.5680	0.3546	0.0031	<0.0001
Treatment	Yield (kg/vine)			Clusters (no./vine)			Yield (kg/vine)			Clusters (no./vine)		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Control	6.3 a	10.2 a	5.9 d	57 a	96 a	47 c	109.8 b	105.0 a	125.2 b	51 a	46 a	40 b
100ET/ $K_c = 0.75$	5.9 a	8.5 c	6.3 cd	50 b	81 b	51 b	107.1 b	102.8 ab	133.8 ab	42 b	46 a	41 b
100ET/ $K_c = 0.5\text{--}0.8$	4.8 b	7.6 c	7.0 bc	45 b	79 b	54 ab	100.8 b	93.7 c	131.5 ab	37 c	45 ab	45 b
150ET/ $K_c = 0.75$	6.5 a	9.4 ab	7.7 ab	48 b	94 a	58 ab	134.3 a	98.1 bc	134.6 ab	48 a	44 b	53 a
150ET/ $K_c = 0.5\text{--}0.8$	6.8 a	8.8 b	8.5 a	49 b	90 a	60 a	136.0 a	97.2 bc	144.1 a	49 a	45 ab	43 b
P value	<0.0001	<0.0001	<0.0001	0.0016	<0.0001	0.0003	<0.0001	<0.0001	0.2566	<0.0001	<0.0001	0.0004

^z1 kg = 2.2046 lb, 1 g = 0.0353 oz.

^yMeans followed by different letters are significant at $P \leq 0.05$ via Duncan's multiple range test.

row, 10 equally spaced vines (approximately every 12th vine) were chosen as data collection points. The experimental block at the Beamsville site consisted of 15 half-rows, each containing 100 vines. A separate valve controlled water supply to each half-row. The trial consisted of three blocks (replicates); as at the Virgil 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, 10 equally spaced vines were used for data collection (approximately every 10th vine).

CALCULATION OF ET_o VALUES:
IRRIGATION SCHEDULING. For determining the vine water requirements for a particular week, weather data from the previous week was collected. The FAO Penman-Monteith equation (Eq. 1) was used to calculate the ET_o for the site based on weather variables. Ontario Weather Network [OWN (now Weather Innovations, Chatham, ON, Canada)] supplied daily weather information such as temperature (maximum, minimum, and average), relative humidity (maximum and minimum), net radiation, precipitation, and wind speed.

$$ET_o (\text{mm} \cdot \text{d}^{-1}) = \frac{[0.408\Delta(R_n - G + \frac{900}{T_{\text{avg}} + 273} \mu_2(e_s - e_a))]}{\Delta + \gamma(1 + 0.34\mu_2)} \quad \text{Eq. [1]}$$

Where,

ET_o = reference evapotranspiration [$\text{mm} \cdot \text{d}^{-1}$],

R_n = net radiation at the crop surface [$\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$],

G = soil heat flux density [$\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$],

T = mean daily air temperature at 2-m height [$^{\circ}\text{C}$],

u_2 = wind speed at 2-m height [$\text{m} \cdot \text{s}^{-1}$],

e_s = saturation vapor pressure [kPa],

e_a = actual vapor pressure deficit [kPa],

$e_s - e_a$ = saturation vapor pressure deficit [kPa],

Δ = slope vapor pressure curve [$\text{kPa}/^{\circ}\text{C}$], and

γ = psychrometric constant [$\text{kPa}/^{\circ}\text{C}$].

The ET_o was then used, along with different crop coefficients (K_c =

0.5–0.8) to calculate the volume of water required by the vines, in liters per vine per day [Eq. 2a and 2b (van der Gulik and Eng, 1987)]. Crop coefficients were determined by measuring the length of the shadow produced by the canopy at solar noon, and expressing this distance as a percentage of row width; hence, a shadow length of 2.0 m and a row width of 2.7 m would result in a K_c of 0.75 (Williams and Ayars, 2005). Examples of measured K_c values for 2005 were: 0.58 (23 June), 0.63 (30 June), 0.67 (7 July), 0.71 (14 July), 0.75 (21 July), and 0.75 (28 July). 0.80 (4 Aug.). The volume requirements were converted to number of hours of irrigation using the mathematical steps taken to schedule irrigation applications described in detail in Reynolds (2008). The calculated amount of water required was then applied to the vineyard the following week from about 20 June (bloom) to 25 Aug. (harvest) 2003, 2004, and 2005. A typical irrigation duration at peak ET_o (about 6 mm in early July) and full canopy (K_c = 0.8) was 9 h, and would have consisted of 2.8 $\text{mm} \cdot \text{d}^{-1}$ (20 mm for the week).

Liters/vine per day

$$= 0.623 \times 3.785 \times ET_o \times S \times A \times K_c \quad \text{Eq. (2a)}$$

Where,

0.623 = 27,152 gal/acre-inch

43,560 ft^2 /acre

3.785 = conversion from gallons to liters

ET_o = reference evapotranspiration ($\text{mm} \cdot \text{d}^{-1}$)

S = soil water storage factor (96 $\text{mm} \cdot \text{m}^{-1}$; see Eq. 2b)

A = grapevine surface area (45 ft^2)

K_c = crop coefficient, and

$S = s \times d \times a$ (Eq. 2b).

Where

(calculated and then read as a unitless value from a table ≈ 0.75):

s = available water storage capacity (200 $\text{mm} \cdot \text{m}^{-1}$)

d = effective rooting depth for grapes (1.2 m), and

a = availability coefficient for grapes (0.40).

Vine and soil water status

SOIL MOISTURE. Soil moisture data were taken weekly in the 2004 growing season, and biweekly in

2003 and 2005 growing seasons, and were measured 2 to 3 d after irrigating the treated vines. Soil moisture levels were evaluated using a soil moisture sensor (Theta Probe model ML2X; Delta-T Devices, Cambridge, UK). Probe readings (cubic meters of water per cubic meter of soil) were taken at each of 10 previously flagged data vines in each treatment replicate. Measurements were taken in the row about 20 cm from the base of each vine trunk. Soil moisture was integrated over a 100-mm depth.

WATER POTENTIAL. Measurements of midday leaf ψ were taken weekly in 2003 and 2004 and biweekly in 2005. Leaf ψ was measured using a model 3005 Plant Water Status Console (Soil Moisture Equipment, Santa Barbara, CA), which applied pressure to a severed leaf with an intact petiole. Leaf ψ measurements were taken from one block (block no. 2 at the Beamsville site and block no. 4 at the Virgil site) from two vines per row and four mature exposed leaves per vine. Leaf blades were initially enclosed in plastic bags before leaf ψ measurement, consistent with Williams and Araujo (2002) and others. Leaf ψ was sampled hourly on cloudless days between 1100 and 1500 HR.

TRANSPIRATION. A steady-state porometer (LI-1600; LI-COR, Lincoln, NE) was used to measure transpiration rate of grapevine leaves at various dates through the growing seasons. The porometer measured leaf temperature, quantum, and g_s , and calculated T_s rate from these data. Leaf T_s rate was computed from dry air flow rate, chamber vapor pressure, leaf saturation vapor pressure, and leaf area. Leaf T_s for all treatments were measured weekly at both sites (2003 and 2004; biweekly in 2005). Five exposed, recently expanded leaves on two vines per row were selected on each vine and were measured hourly between 1100 and 1600 HR, giving a total of 10 readings per treatment per day of measurement. The purpose of taking hourly measurements between 1100 and 1600 HR was to capture the peak T_s rate, usually at midday, and to monitor how T_s rates progressed for each treatment through the course of the day. Measurements were made 2 to 3 d after irrigating the treatments.

HARVEST AND BERRY SAMPLING:
VINE SIZE. Harvest occurred on 4 to 6 Sept. 2003, 1 to 3 Sept. 2004, and 20 to 22 Aug. 2005 at the Virgil site; and 2 to 4 Sept. 2003, 23 to 25 Aug. 2004, and 24 to 26 Aug. 2005 at the Beamsville site. Before harvest, 100-berry samples were collected randomly from each of the 250 marked experimental vines at the Virgil site and the 150 marked experimental vines at the Beamsville site. After collection, these samples were placed in plastic bags and stored at -25°C for later analysis. Additional 300-berry samples were collected from each treatment replicate to measure concentrations of methyl anthranilate and total volatile esters. Clusters per vine were counted and yield per vine was determined as grapes were harvested. Cluster weight was calculated from yield per vine and clusters per vine data. Berries per cluster were estimated from cluster weight and berry weight data. Weight of cane prunings (vine size) was collected annually during dormant pruning by weighing the prunings using an electronic scale.

STANDARD BERRY COMPOSITION. Before analysis, each 100-berry sample was weighed using a digital balance. Each sample was placed in 250-mL beakers, heated at 80°C in a water bath (Fisher Scientific, Mississauga, ON, Canada) to redissolve tartrates that precipitated during freezing, and then blended in a centrifugal juicer (Omega 9000; Pleasant Hill Grain, Aurora, NE). Samples were then left to settle about 30 min before the percentage of soluble solids were measured using a refractometer (American Optical Abbé model 10450; AO Corp., Buffalo, NY). The pH was measured with a pH meter (Fisher Scientific Accumet model AB15). Titratable acidity (expressed as tartaric acid equivalents in grams per liter) was measured using a 5.0-mL aliquot of juice titrated with 0.1 N sodium hydroxide with an automated titration system (PC Titrate; Man-Tech, Guelph, ON, Canada). All techniques of measurement were consistent with those described in Zoecklein et al. (1995).

BERRY ANALYSIS FOR COLOR, ANTHOCYANINS, AND PHENOLS. After TA measurements, an aliquot of each juice sample was centrifuged at $6000 g_n$ for 10 min using a centrifuge (Centra CL2; International

Equipment Co., Needham Heights, MA), placed in 20-mL plastic bottles, and stored at -25°C for later analysis for anthocyanins, color, and phenols. The samples were again heated at 80°C in a water bath (Fisher Scientific) to redissolve tartrates that precipitated during freezing. Each sample was then filtered through a syringe membrane filter ($0.45\text{-}\mu\text{m}$, HV Dura-pore; Millipore, Bedford, MA). Color was measured by absorbance of the centrifuged juice at 420 nm (A420) and 520 nm (A520) in a 10-mm glass cuvette using an ultraviolet/VIS spectrophotometer [Pharmacia Biotech Ultrospec 1000E; Biochrom, Cambridge, UK (used for all subsequent spectrophotometric measurements)]. 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 was used as a blank to calibrate the spectrophotometer. The hue (A420/A520) and intensity of color (A420 + A520) were calculated from these data. The anthocyanins were measured by the pH shift method (Fuleki and Francis, 1968) as described in detail by Reynolds et al. (2005b) by setting up two sets of test tubes in duplicate for each sample. Absorbance was determined using a 10-mm glass cuvette and an ultraviolet/VIS spectrophotometer at a wavelength of 520 nm, and the anthocyanin concentration was calculated from these data. Phenols were measured by the Singleton and Rossi method (1965) as described in detail by Reynolds et al. (2005b) using 1 mL of juice, which was added to 9 mL of distilled water. The absorbance of the solutions was determined using a 10-mm glass cuvette in an ultraviolet/VIS spectrophotometer at 765 nm.

BERRY ANALYSIS FOR METHYL ANTHRANILATE AND TOTAL VOLATILE ESTERS. Analysis for MA and TVE was done as described by Fuleki (1982). 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 30 s, and four 50-g subsamples were then weighed out and distilled using an apparatus that consisted of a round bottom steam-generating flask, a distillation flask, and a condensing column (Lurex, Vineland, NJ). Within 15 to 20 min, the first 100 mL of distillate was collected into a 100-mL volumetric flask and stored at

4°C . The same distillate was used to determine MA and TVE concentrations. MA standards were prepared from a stock solution of $100\text{ mg}\cdot\text{L}^{-1}$ MA, which was then used to prepare eight standard solutions of concentrations ranging from 0.1 to $10\text{ mg}\cdot\text{L}^{-1}$. MA concentration was determined via a luminescence spectrophotometer (model LS50; Perkin-Elmer, Boston) that was set at an emission wavelength of 420 nm with an 8.0-nm slit width, and an excitation of 325 nm and a 5.0-nm slit width. The fluorescence of MA was read directly, while the MA concentration was determined by a standard curve. TVE were determined through a colorimetric reaction described by Hill (1946), described in detail by Reynolds et al. (2005a). Absorbance readings of all standards and samples were carried out on an ultraviolet/VIS spectrophotometer at 540 nm. Thereafter, TVE concentrations were extrapolated from a standard curve.

Statistical analysis

All data were analyzed using SAS (version 9.1; SAS Institute, Cary, NC). The General Linear Models procedure (PROC GLM) was used. Duncan's multiple range test was used to determine significant differences among treatments. Dunnett's *t* test was used to determine those treatments that were different from the nonirrigated control (Dunnett, 1955).

Results and discussion

Rainfall and reference evapotranspiration

Rainfall in 2003 was characterized by several significant precipitation events in mid to late June, mid-July, and also in early August, but most of the remainder of the season was relatively dry (Fig. 1). The 2004 season had the most consistent rainfall, including frequent events throughout much of July and August. Low ET_o values experienced in 2004 were due to the several rain events that resulted in cloudy, humid, and cool conditions (Figs. 1 and 2). In contrast, 2005 was a very dry season. As expected, ET_o rates were generally greatest from late June to mid-Aug. 2005 (Fig. 2) when temperatures were at their annual high and solar radiation was at its maximum. ET_o values were therefore highest in 2005, particularly in the early

Fig. 1. Daily rainfall values from June through Aug. 2003 to 2005 at the Ontario Weather Network weather station in Virgil, ON, Canada (1 mm = 0.0394 inch).

Fig. 2. Daily evapotranspiration (ET) values from June through Aug. 2003 to 2005 based on data accessed from the Ontario Weather Network weather station in Virgil, ON, Canada (1 mm = 0.0394 inch).

summer months due to the high temperatures (30.3–32.8 °C), and decreased as the season progressed (Fig. 2). Although Summer 2004 was quite wet, irrigation was still required during most weeks. There were only three times when no irrigation was needed in the 2003 and 2004 growing seasons because adequate amounts of water (>12 mm; van der Gulik and Eng, 1987) were provided by rainfall (Fig. 1): once in 2003 (7 July) and twice in 2004 (7 July and 11 Aug.).

Weather data indicated that the ET_o for the Niagara region was

highest in the 2005 growing season and was lowest in 2004. Season-long (buddburst to mid-Oct.) ET_o values were 852 mm (2003), 659 mm (2004), and 1241 mm (2005) throughout the study. The 2005 value is very similar to typical ET_o values for Fresno, CA, which are reported as 1173 mm (Williams et al., 2003) and those throughout much of central California, which range from 1072 to 1289 mm (Williams and Baeza, 2007). The general trend in ET_o was a rise from mid-June to a peak in mid-July and early August, followed by a

decline for the remainder of the growing season. In midsummer when temperatures were high and relative humidity was low, the water demand by the vines increased as result of these the climatic conditions (Williams and Matthews, 1990). Therefore, increases in ET_o rates were mainly a function of solar radiation, which was at its maximum in late June to mid-July. Particularly high daily ET_o values were recorded during the very dry weather and high solar radiation in the 2005 growing season. Low ET_o values in 2004 were due to several rain events that resulted in cloudy, humid, and cool conditions.

As the vine canopy size increased, so did the plant water requirements, consistent with studies elsewhere (Williams and Matthews, 1990). The use of data from OWN from the previous week, along with two different K_c values of 0.75 or 0.5 to 0.8 (based on canopy volume), were together adequate in calculating irrigation needs. Based upon leaf ψ and soil moisture values, irrigation was definitely needed in the Summer 2003 and 2005 as it was in previous dry seasons such as 2001 and 2002 (Reynolds et al., 2005a, 2007), but irrigation was also beneficial at certain points in 2004 despite rain events. The practice of using the previous week's ET_o to calculate the amount of water to apply during the upcoming week's irrigation worked well in dry years such as 2003 and 2005. A potential disadvantage to this method, however, occurs if a large amount of precipitation was received between irrigations, reducing the ET_o and, consequently, the water volume required for the upcoming week.

Vine and soil water status

SOIL MOISTURE. Differences in soil moisture between irrigated and nonirrigated treatments occurred throughout the experiment, and higher moisture levels were usually measured in irrigated treatments in all 3 years of the study. Irrigation normally supplied the vines with adequate water to maintain soil moisture levels consistently above the wilting point (13.3% and about 25.0% soil moisture by volume for Virgil and Beamsville sites, respectively), but considerably below field capacity (27.3% and about 42.3% soil moisture for Virgil and Beamsville sites, respectively)

(Kingston and Presant, 1989). In general terms, soil moisture values were between 15% and 27% soil moisture at the Virgil site and 15% and 35% at the Beamsville site.

Soil moisture values at the Virgil site in 2003 were consistently above the wilting point, and the nonirrigated treatment had the lowest

values. The mid-August (19 Aug.) sampling had the lowest soil moisture values (Fig. 3A). In 2004, soil moisture values (Fig. 3B) were between wilting point and field capacity (or slightly above); this was possibly due to the rainfall that year (Fig. 1). Although these rain events decreased the magnitude of difference between

the irrigated and nonirrigated treatments, irrigated treatments still had higher soil moisture than nonirrigated treatments. Soil moisture was typically higher in the irrigated treatments in 2005 as well. The middle of the growing season had the lowest soil moisture values from 14 July to 1 Aug. and actually fell below

Fig. 3. Impact of irrigation treatments on soil moisture of 'Sovereign Coronation' grapevines at Virgil, ON, Canada in 2003 (A), 2004 (B), and 2005 (C); or Beamsville, ON, Canada in 2003 (D), 2004 (E), and 2005 (F). Treatments were not irrigated (control); 100% reference evapotranspiration (ET_o) with a fixed ($K_c = 0.75$; 100/0.75) or variable crop coefficient ($K_c = 0.5-0.8$; 100/VAR); 150% ET_o with a fixed (150/0.75) or variable K_c value (150/VAR).

wilting point, but by the end of the season, the soil moisture was high, due possibly to a mid-August rain event (Fig. 3C). In general, soil moisture in 2005 was low relative to 2003 and 2004 because of a lack of precipitation and high temperatures.

At the Beamsville site in 2003, the lowest soil moisture was recorded early to midpoint in the growing season and was below wilting point (2–25 July) (Fig. 3D). These low values can be attributed to the short probe length on the soil moisture sensor. Almost all treatments were above the wilting point in the latter part of the season, while the non-irrigated treatment had the lowest values all season. In 2004, all treatments had higher soil moisture values than 2003, yet the control still was below wilting point throughout the season, as were other treatments on 29 June and throughout much of early to mid-August (Fig. 3E). In 2005, soil moisture values on all sampling dates at the Beamsville site were below wilting point, where soil moisture fell to as low as 6.8% soil moisture in irrigated treatments, and the nonirrigated treatments were 5.2% soil moisture (Fig. 3F). These low values can again be attributed to the short probe length (100 mm) on the soil moisture sensor. The irrigated treatments were still relatively higher in soil moisture content during that period compared with the nonirrigated treatment.

Soil moisture levels typically declined as each growing season progressed. Higher soil moisture levels were observed at both sites and on almost all sampling dates in irrigated treatments compared with nonirrigated vines in all 3 years of the study. Soil moisture was below wilting point in irrigated treatments on two sampling dates at one site in 2003, but this was rectified later in the season. Irrigation usually supplied adequate water to maintain soil moisture levels consistently above the wilting point and below the field capacity for the soils in question (Kingston and Presant, 1989). High rainfall events in 2004 caused soil moisture levels for all the treatments including those nonirrigated treatments 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 nonirrigated treatments in that year. However, it was still clear that irrigated treatments still had higher soil moisture than nonirrigated treatments in that year. All treatments at the Beamsville site had very low in soil moisture in the 2005 growing season, and were frequently below the wilting point (25%) for the Morley clay (Kingston and Presant, 1989). These values were above the 14.8% soil moisture value measured in a drought-stressed 'Concord' vineyard in Honeoye gravelly sandy loam soil in New York state (Poni et al., 1994); however, that soil type has a much lower wilting point than the Morley clay.

WATER POTENTIAL. In general, treatment differences in leaf ψ occurred at both sites in almost every week throughout the growing season. The most negative leaf ψ values (<-14 bars) were found in all treatments in the first week of 2003 at the Virgil site (Fig. 4A). In fact, leaf ψ dropped to ≤ -13 bars throughout 2003, which confirmed that water stress was likely present in nonirrigated vines. Low leaf ψ (<-12) were also found near the end of the 2004 growing season at the Virgil site in all treatments (Fig. 4B). In 2005, mean leaf ψ was as low as -13 bars but only in the nonirrigated treatment, whereas in all irrigated treatments, ψ was ≥ -12 bars. At the end of the 2005 growing season, leaf ψ in all treatments increased; ψ was ≥ -8 , even in the nonirrigated treatment, perhaps due to the rain event that occurred that week; this corresponded with high soil moisture values measured that week (15 Aug.) (Fig. 4C).

Differences among treatments for leaf ψ were likewise detected on all sampling dates in 2003 at the Beamsville site. However, leaf ψ was very low early in the season. The nonirrigated treatment had leaf ψ as low as -16 bars (Fig. 4D). In 2004, although the year was wet, the absolute values of leaf ψ were high. With one exception (3 Aug.), all treatments had leaf ψ values ≤ -13 bars, with the nonirrigated treatment having the lowest values where ψ dropped to -16 in 1 week (27 July) (Fig. 4E). In 2005, irrigated vines were rarely ≤ -11 bars, whereas for nonirrigated vines, leaf ψ was <-13 bars early in the season. Hence, irrigated vines likely

never experienced significant water stress that season because irrigation consistently increased leaf ψ and maintained it above -11 bars (Fig. 4F).

Water stress is generally recognized to occur when the leaf ψ decreases to <-12 bars, which causes partial stomatal closure (Smart and Coombe, 1983). Mild water stress is normally considered desirable for red wine grapes, but it is unlikely to be of benefit for table grapes. In the present study, differences between treatments for leaf ψ occurred almost every week throughout the three growing seasons, and the data followed a trend whereby leaf ψ remained low throughout the season for nonirrigated treatments. Leaf ψ was in fact <-12 bars in nonirrigated treatments at both sites on almost every sampling date, which confirmed that water stress was present in the vines. Specifically, in 2005, mean leaf ψ was as low as -14 bars but only in nonirrigated treatments at both sites. This was likely due to increased water demand that resulted from the expanding canopy, combined with a lack of water applied to the vines (Reynolds et al., 2007; Smart, 1974; Williams and Matthews, 1990). These results again confirmed that irrigation was beneficial in the dry summers experienced in 2003 and 2005.

TRANSPIRATION. Overall, irrigated vines had the highest T_s rates. In 2003 at the Virgil site, T_s rate was low in all treatments, with the nonirrigated treatment having the lowest value for the season (13 July), and, a trend appeared whereby the T_s rate increased as the season progressed (Fig. 5A). In 2004, T_s rates for all treatments were generally higher than in 2003. This was presumably due to several rainfall events in 2004, although irrigated vines were still higher than control vines (Fig. 5B). In the dry 2005 season, irrigation increased T_s rates, and the irrigated treatments showed highest T_s on all dates, while nonirrigated treatments transpired least (4 and 18 July and 1 Aug. 2005) (Fig. 5C). In 2003 and 2005, supplemental irrigation occasionally could not raise T_s rates (Fig. 5, A and C).

Generally, irrigated vines had the highest T_s rates at the Beamsville site also (Fig. 5, D–F). In 2003, the T_s rates were very low in all treatments,

Fig. 4. Impacts of irrigation on leaf water potential (ψ) of 'Sovereign Coronation' grapevines at Virgil, ON, Canada in 2003 (A), 2004 (B), and 2005 (C); or Beamsville, ON, Canada in 2003 (D), 2004 (E), and 2005 (F). Treatments were not irrigated (control); 100% reference evapotranspiration (ET_o) with a fixed ($K_c = 0.75$; 100/0.75) or variable crop coefficient ($K_c = 0.5-0.8$; 100/VAR); 150% ET_o with a fixed (150/0.75) or variable K_c value (150/VAR); 1 bar = 0.1 MPa.

and nonirrigated vines transpired the least on most sampling dates, with the lowest values occurring midseason (4 July); however, there were no differences between irrigated and nonirrigated vines on that sampling date. The T_s rate increased as the season progressed, with nonirrigated vines generally transpiring least (Fig.

5D). In 2004, T_s rates for all treatments were higher than 2003. This was due somewhat to rainfall events in 2004 (Fig. 1), but irrigated treatments were still higher than control treatments (Fig. 5E). Irrigation increased T_s rates in 2005; on 4 and 18 July 2005, nonirrigated vines were transpiring least (Fig. 5F). All

treatments resulted in low T_s rates midseason, but by the end of the season, all treatments had high E , and the nonirrigated treatment was always lowest. These results suggested that there was low water status in nonirrigated treatments.

The nonirrigated treatments at both sites transpired at lower rates than

Fig. 5. The impact of irrigation treatments on leaf transpiration (T_s) rate of 'Sovereign Coronation' grapevines at Virgil, ON, Canada in 2003 (A), 2004 (B), and 2005 (C); or Beamsville, ON, Canada in 2003 (D), 2004 (E), and 2005 (F). Treatments were not irrigated (control); 100% reference evapotranspiration (ET_o) with a fixed ($K_c = 0.75$; 100/0.75) or variable crop coefficient ($K_c = 0.5$ – 0.8 ; 100/VAR); 150% ET_o with a fixed (150/0.75) or variable K_c value (150/VAR); $1\text{ }\mu\text{g}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}\text{H}_2\text{O} = 2.2757 \times 10^{-7}\text{ oz/inch}^2$ ($\text{H}_2\text{O} = \text{water}$).

the irrigated treatments on most sampling dates. The irrigated treatments showed the consistently-highest T_s rates (7 – $18\text{ }\mu\text{g}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$) on almost all sampling dates, whereas nonirrigated treatments transpired lowest (4 – $10\text{ }\mu\text{g}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$), suggesting that water stress was potentially present. The differences in T_s rate throughout

all three seasons can be attributed to the weather patterns throughout the growing seasons. Transpiration rates were higher in 2004 compared with 2003 and 2005, due to adequate and timely precipitation. For this reason, the trend during that season was relatively small differences in T_s rates between treatments throughout the

season. In 2003 and 2005, vines experienced severe droughts and supplemental irrigation occasionally could not raise T_s rates. In drought situations, vines may osmoregulate and shut down their gas exchange systems to conserve resources and nutrients (Düring, 1990). This might explain why, even when supplied with water,

the irrigated vines did not transpire at substantially higher rates than the nonirrigated vines on certain sampling dates. However, under most cases, nonirrigated treatments had substantially lower T_s rates and thus endured more water stress, and this concurs with other studies (Choné et al., 2001; Fuller, 1997; Gomez-del-Campo et al., 2002; Reynolds et al., 2007).

YIELD COMPONENTS. Irrigation had a considerable positive relationship with on yield in 2005 but not in 2003 or 2004. Yield increased in 2005 in all irrigation treatments at the Virgil site, whereby yield increased by about 10% to 27%, relative to the nonirrigated treatment, with the 150ET treatments yielding highest (Table 1). A similar trend occurred in 2005 at the Beamsville site where the irrigated treatments had 6% to 30% higher yields relative to the nonirrigated 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 Virgil site increased by 13% to 27% in irrigated treatments, with the 150ET treatments being superior. Clusters per vine at the Beamsville site increased in irrigated treatments by 8% to 22%, with the 150ET treatments again being superior. Cluster weight occasionally increased in some irrigated treatments relative to the nonirrigated treatment. In 2003 at the Virgil site, there was a trend for all irrigated treatments to exceed the nonirrigated treatment (3%–19% increases), although only the 100ET/0.5–0.8 treatment was significantly different. Cluster weights did not increase with irrigation at the Virgil site in 2004 or 2005. The Beamsville site, however, showed increases in cluster weights in two of four irrigated treatments in 2003 and one of four in 2005; cluster weights increased in the 150ET treatments by about 19% relative to the nonirrigated treatment in 2003, and all the irrigated treatments showed increasing trends (5%–13%) relative to the nonirrigated treatment. Although there were some differences between treatments at the Virgil site in 2004 and 2005, there were no obvious benefits of irrigation in terms of berries per cluster. There were similar responses at the Beamsville site in 2003 and 2004, but there was a 24% increase in berries per cluster in 2005 in the

150ET/0.75 treatment relative to the nonirrigated treatment.

There was an increase in overall yield in irrigated treatments in some seasons. About 10% to 30% increases in yield occurred in most irrigated treatments compared with the nonirrigated vines. Clusters per vine also increased 10% to 27% in 2005 at both sites in the irrigated treatments over the nonirrigated treatment. Cluster weights also increased slightly in some irrigated treatments over the nonirrigated treatment; in the 2003 and 2004 seasons, the cluster weight increased by about 3% to 19% in some irrigated treatments. Berries per cluster showed no response to irrigation in 2003 and 2004 at the Beamsville site, but there was an increase there in 2005 and in 2003 and 2005 (as high as 24% in some irrigated treatments) at the Virgil site. Of greatest importance were the increases in berry weight associated with irrigation. A possible explanation for these results is that water supply resulted in more fertile buds, leading to a higher overall cluster number. Studies on *V. labruscana* and *V. vinifera* cultivars in Ontario have proven that irrigation increases yield and berry weight substantially over nonirrigated treatments (Cline et al., 1985; Reynolds et al., 2005a, 2007).

VINE SIZE. The weight of cane prunings did not increase in the irrigated treatments in 2003 at the Virgil site but were increased by irrigation in 2003 and 2004 at the Beamsville site

(Table 2). In 2005, none of the irrigated treatments exceeded the nonirrigated treatment, and one (100ET/0.75) had substantially lower vine size (Table 2). This increase in vine size in irrigated treatments was as high as 74% over the nonirrigated treatments. This corresponds with more vigorous shoots and concomitant increases in yield. The only potential benefits of lower vine size in nonirrigated treatments might be the reduction in pruning costs for the grower, as well as the possibility of reduced canopy shade (Smart et al., 1985).

BERRY WEIGHT. Irrigation had clear positive effects on berry weight at both sites, whereby the irrigated treatments were generally higher in berry weight than nonirrigated treatment for all three seasons (Table 3). At the Virgil site, the berry weight was increased 10% to 14% by the irrigated treatments in 2004 and 2005 relative to nonirrigated treatments. There were no effects on berry weight in 2003 at the Virgil site. At the Beamsville site, irrigation increased berry weights by 16% to 23% over nonirrigated treatment in 2003, by 11% to 16% in 2004, and by 15% to 29% in 2005. In practically each case, the 150ET treatments produced highest berry weights. Overall, irrigation increased berry weight by nearly 15% to 20% in most irrigated treatments at both sites compared with the nonirrigated treatments. This is in agreement with other research that has shown that increased irrigation

Table 2. Impact of irrigation treatments on weight of cane prunings (vine size; kg/vine) of ‘Sovereign Coronation’ table grapes at Virgil and Beamsville, ON, Canada in 2003 to 2005. Treatments were not irrigated (control); 100% reference evapotranspiration [ET_o (100ET)] with a fixed crop coefficient ($K_c = 0.75$) or a variable one ($K_c = 0.5$ – 0.8); 150% ET_o (150ET) with a fixed or variable K_c value. Boldfaced data indicate those values significantly different from the nonirrigated control, Dunnett’s t test; those boldfaced and underlined are significantly less than the control. Data were unavailable from the Lambert site in 2004 and 2005.

Treatment	Vine size (kg/vine) ^z			Virgil, ON
	Beamsville, ON			
	2003	2004	2005	2003
Control	0.16 b ^y	0.24 b	0.53 ab	0.95
100ET/ K _c = 0.75	0.26 a	0.27 b	0.29 c	1.05
100ET/ K _c = 0.5–0.8	0.28 a	0.29 b	0.30 bc	1.03
150ET/ K _c = 0.75	0.29 a	0.39 a	0.69 a	1.01
150ET/ K _c = 0.5–0.8	0.33 a	0.45 a	0.35 bc	1.00
<i>P</i> value	0.0005	<0.0001	0.0009	0.8999

^z1 kg = 2.2046 lb.

^yMeans followed by different letters are significant at $P \leq 0.05$ via Duncan’s multiple range test.

Table 3. Impact of irrigation treatments on berry weight, soluble solids, titratable acidity, and pH of 'Sovereign Coronation' table grapes at Virgil and Beamsville, ON, Canada in 2003 to 2005. Treatments were not irrigated (control); 100% reference evapotranspiration [ET_o(100ET)] with a fixed crop coefficient ($K_c = 0.75$) or a variable one ($K_c = 0.5-0.8$); 150% ET_o (150ET) with a fixed or variable K_c value. Boldfaced data indicate those values significantly different from the nonirrigated control, Dunnett's *t* test; those boldfaced and underlined are significantly less than the control.

Virgil, ON											
Treatment	Berry wt (g) ^z			Total soluble solids (%)			Titratable acidity (g·L ⁻¹) ^y			pH	
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2005
Control	3.00	2.79 c ^y	3.37 c	15.6 b	14.9 c	18.3 c	15.5 b	13.4 a	16.1 a	3.18 a	3.22 d
100ET/ K _c = 0.75	2.99	3.13 b	3.82 b	15.5 bc	15.3 bc	18.9 b	15.2 b	12.7 b	15.7 b	3.17 ab	3.30 c
100ET/ K _c = 0.5–0.8	2.99	3.18 b	3.83 b	15.5 bc	16.4 ab	18.9 b	16.3 a	12.5 b	15.6 b	3.15 b	3.33 b
150ET/ K _c = 0.75	3.06	3.14 b	3.90 ab	16.5 a	16.0 abc	19.5 a	14.5 c	12.0 c	15.0 c	3.17 ab	3.36 ab
150ET/ K _c = 0.5–0.8	2.99	3.25 a	3.93 a	15.2 c	16.9 a	19.4 a	16.1 a	11.8 c	14.9 c	3.16 ab	3.38 a
<i>P</i> value	0.1694	0.0063	<0.0001	<0.0001	0.0057	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Beamsville, ON											
Treatment	Berry wt (g)			Total soluble solids (%)			Titratable acidity (g·L ⁻¹)			pH	
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2005
Control	2.18 d	2.71 c	2.52 c	19.6 b	18.8 c	12.6 c	11.2 c	13.3 a	13.4 a	3.16 a	3.16 c
100ET/ K _c = 0.75	2.59 c	3.05 b	3.11 b	19.5 b	20.6 d	20.0 b	14.1 a	12.3 b	13.1 b	3.14 b	3.27 b
100ET/ K _c = 0.5–0.8	2.72 b	3.09 b	2.99 b	20.0 a	21.3 c	19.9 b	12.9 b	12.5 b	12.7 c	3.12 c	3.27 b
150ET/ K _c = 0.75	2.85 a	3.22 a	3.49 a	19.4 b	21.7 b	20.3 a	12.7 b	11.9 c	12.2 d	3.07 d	3.31 a
150ET/ K _c = 0.5–0.8	2.78 ab	3.19 ab	3.53 a	19.5 b	22.0 a	20.2 ab	13.0 b	11.6 d	12.2 d	3.07 d	3.33 a
<i>P</i> value	<0.0001	0.0181	<0.0001	0.0523	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^z1 g = 0.0353 oz, 1 g·L⁻¹ = 0.1 %.

^yMeans followed by different letters are significant at $P \leq 0.05$ via Duncan's multiple range test.

application results in higher berry weights (Reynolds et al., 2007; Williams and Matthews, 1990). Berry weight consistently appeared to be the main factor contributing to the increased yields.

Standard berry composition

SOLUBLE SOLIDS. Juice soluble solids were generally higher in irrigated treatments than in nonirrigated treatments for all 3 years at the Virgil site (Table 3). The 150ET/0.75 treatment was the highest in 2003 but the other 150ET treatment resulted in lowest soluble solids in the same year. In 2004, the non-irrigated treatment had the lowest soluble solids, and two of four irrigated treatments exceeded it. The same trend occurred in 2005 at the Virgil site, where all irrigated treatments produced soluble solids higher than the non-irrigated treatment. This likewise occurred at the Beamsville site, where irrigation treatments increased soluble solids over the non-irrigated treatment in 2004 and 2005 (Table 3). The highest soluble solids occurred in the 150ET treatments, and specifically in 2004, where the berries measured 22% soluble solids in the 150ET/0.5–0.8 treatment.

In general, soluble solids were higher in irrigated treatments than in nonirrigated treatments over the 3 years. The greatest soluble solids accumulation occurred in 2004 at the Beamsville site, where the 150ET/0.5–0.8 treatment had 22% soluble solids (14% more than the nonirrigated treatment). It is sometimes assumed that larger berries automatically would have lower soluble solids than smaller berries due to an increase in water content. However, results from this and previous studies (Ginestar et al., 1998; Reynolds et al., 2007) showed that this is not always the case. It is likely that water-stressed nonirrigated treatments experienced reduced Ts rates, and therefore gas exchange in general was compromised, including photosynthesis, the source of sucrose. This possible reduction in photosynthesis could explain the lower soluble solids in many of the low- or nonirrigated treatments.

TITRATABLE ACIDITY AND pH. Titratable acidity increased in response to the two irrigated treatments with K_c 0.5–0.8 in 2003 at the Virgil

site but decreased with irrigation in 2004 and 2005 (Table 3). The 150ET treatments resulted in the lowest TA in 2004 and 2005. The lowest TA across all 3 years at the Virgil site occurred in 2004 in the 150ET/0.5–0.8 treatment (11.8 g·L⁻¹). The Beamsville site, on the other hand, had lowest TA in the nonirrigated treatment in the 2003 season, which was coincidentally the lowest TA across all 3 years at that site (11.2 g·L⁻¹ compared with 14.1 g·L⁻¹ in the 100ET/0.75 treatment that year). As at Virgil, TA at the Beamsville site was lowest in response to irrigation in 2004 and 2005. Therefore, overall the TA values for the irrigated treatments were generally higher than the nonirrigated treatment in 2003 in the Virgil site but decreased with irrigation in 2004 and 2005 at both sites. It is likely that water uptake into the berries diluted some of the organic acids in 2004 and 2005 (Mullins et al., 1992). Water stress can delay fruit maturation without degradation of organic acids (McCarthy, 1999; Mullins et al., 1992; Reynolds and Naylor, 1994). Irrigation can also delay fruit maturity; the TA of irrigated ‘Chardonnay’ (*V. vinifera*) grapes in Ontario generally was higher than in nonirrigated treatments (Reynolds et al., 2007).

Berry pH at the Virgil site was affected little by irrigation in 2003. However, in 2004, all irrigated treatments caused a slight decrease in pH relative to the nonirrigated treatment, whereas in 2005, the pH increased in response to irrigation. The same general trend occurred as well at the Beamsville site in 2004 and 2005. Unlike the Virgil site, pH decreased at the Beamsville site in 2003 in response to irrigation. Overall, berry pH showed statistically significant but not agriculturally significant decreases in irrigated treatments. The nonirrigated treatment had the highest pH in the 2003 and 2004 growing seasons in both sites. This agrees with others reporting that nonirrigated treatments had slightly higher pH than irrigated treatments (Ligetvari, 1986; Reynolds et al., 2007). In the 2005 season, pH increased in the irrigated treatments over nonirrigated treatments in both sites. It may be possible that increased sun exposure in nonirrigated vines, resulting from reduced vigor caused by

lower water availability, might have caused this pH reduction (Mullins et al., 1992).

Color and phenolic analytes

ABSORBANCE. In general, hue increased under the irrigated treatments in both sites in all three seasons (Table 4). This increase was more pronounced during 2003 at the Virgil site where the 150ET/0.75 treatment resulted in the maximum hue value attained (0.95), whereas the nonirrigated treatment hue was only 0.58 in the same growing season. Two of four and three of four irrigation treatments exceeded the nonirrigated treatment in 2004 and 2005, respectively. At the Beamsville site, two of four irrigation treatments exceeded the nonirrigated treatment in terms of hue in 2003, and only one (150ET/0.5–0.8) was higher here in each of the following two seasons. The hue values of grapes from the vines at the Virgil site tended to be slightly higher than those from vines at the Beamsville site.

Color intensity followed an increasing trend with volume of irrigation in 2004 and 2005 but not 2003. At the Virgil site, color intensity in response to the 150ET/0.75 exceeded the nonirrigated treatment in 2003, but other irrigated treatments were lower. No effects were observed in 2004, while in 2005, three of four irrigated treatments exceeded the nonirrigated treatment. At the Beamsville site, the nonirrigated treatment exceeded all irrigated treatments in color intensity in 2003, but one treatment (150ET/0.5–0.8) exceeded the nonirrigated treatment in 2004, while all irrigated treatments exceeded the nonirrigated treatment in 2005. The intensity values for the Beamsville site were slightly higher than the values for vines at the Virgil site over the three growing seasons. In general, color intensity showed a trend toward higher values in irrigated treatments over nonirrigated treatments, particularly in 2005. This is could be due to the very dry conditions and higher temperatures during that season. These trends agreed with studies on ‘Tempranillo’ (*V. vinifera*), where an increase in color intensity in irrigated vines was reported (Esteban et al., 2001); they also suggested that the intensity value depends on the

seasonal conditions during the study year. Because it is also plausible that berry temperatures on nonirrigated vines were higher than those of irrigated treatments, this factor alone might explain higher color values in nonirrigated treatments (Spayd et al., 2002; Tarara et al., 2008).

ANTHOCYANINS. Irrigation also had an effect on anthocyanin accumulation. In the 2003 season, the nonirrigated treatments had the highest anthocyanin concentration at both sites, while the 150ET/0.75 and the 100ET/0.5–0.8 treatments were the second-highest in anthocyanins at the Virgil and Beamsville sites, respectively (Table 4). This is consistent with other studies showing that anthocyanins in skins of berries from high-yielding irrigated vines were lower than those from low-yielding nonirrigated vines (Esteban et al., 2001; Freeman et al., 1980; Mullins et al., 1992). The likelihood of higher berry temperatures in the nonirrigated treatments might also explain higher anthocyanin concentrations (Spayd et al., 2002; Tarara et al., 2008). The nonirrigated treatment exceeded the irrigated treatments in 2004 at the Virgil site also, but two treatments (both 150ET) exceeded the nonirrigated treatment in 2005. At the Beamsville site, three of four irrigated treatments exceeded the nonirrigated treatment in 2004 and 2005. The total anthocyanins therefore showed trends toward increases in irrigated treatments in the 2005 season at both sites and in 2004 at the Beamsville site. The 2004 and 2005 results were consistent with studies concluding that supplemental water increased anthocyanin development in red grape cultivars (Esteban et al., 2001). In 2003, anthocyanin concentrations from vines at the Virgil site were higher than those from vines at the Beamsville site in all treatments except the nonirrigated vines.

TOTAL PHENOLS. Total phenols showed no consistent response to irrigation in 2003 (Table 4). Two of four irrigated treatments exceeded the nonirrigated treatment at the Virgil site, and only one of four was higher at the Beamsville site. Phenols decreased in response to all irrigated treatments at both sites in the 2004 season. All four irrigated treatments were higher in total phenols at both

Table 4. The impact of irrigation treatments on anthocyanins, total phenols, intensity, and hue of 'Sovereign Coronation' table grapes at Virgil and Beamsville, ON, Canada in 2003–05. Treatments were not irrigated (control); 100% reference evapotranspiration [ET_0 (100ET)] with a fixed crop coefficient ($K_c = 0.75$) or a variable one ($K_c = 0.5$ – 0.8); 150% ET_0 (150ET) with a fixed or variable K_c value. Boldfaced data indicate those values significantly different from the nonirrigated control, Dunnett's t test; those boldfaced and underlined are significantly less than the control.

Treatment	Virgil, ON					
	Anthocyanins (mg·L ⁻¹) ^a			Total phenols (mg·L ⁻¹)		Hue
	2003	2004	2005	2003	2004	
Control	389.1 a ^b	392.1 a	302.9 b	916.5 d	1186.9 c	1614.8 a
100ET/ $K_c = 0.75$	340.7 c	329.3 c	303.7 b	1067.6 c	1171.3 c	1589.5 b
100ET/ $K_c = 0.5$ – 0.8	365.9 b	232.3 c	327.7 b	1122.9 b	1157.6 c	1485.9 c
150ET/ $K_c = 0.75$	388.1 ab	321.0 c	359.5 a	1281 a	1224.3 b	1266.3 d
150ET/ $K_c = 0.5$ – 0.8	347.5 c	374.9 b	367.3 a	1144.6 b	1299.4 a	1453.6 c
P value	<0.0001	<0.0001	<0.0001	<0.0001	0.0006	<0.0001
Treatment	Beamsville, ON					
	Anthocyanins (mg·L ⁻¹)			Total phenols (mg·L ⁻¹)		Hue
	2003	2004	2005	2003	2004	
Control	399.8 a	341.1 c	313.6 d	1623.3 d	1492.7 c	1935.5 a
100ET/ $K_c = 0.75$	288.2 c	349.5 c	331.7 cd	1747.7 ab	1597.2 b	1916.2 a
100ET/ $K_c = 0.5$ – 0.8	337.6 b	358.8 b	356.4 bc	1855.1 a	1885.3 a	1884.5 b
150ET/ $K_c = 0.75$	232.3 d	370.0 b	384.1 ab	1411.1 c	1416.3 c	1834.8 b
150ET/ $K_c = 0.5$ – 0.8	281.7 c	389.3 a	397.1 a	1669.6 ab	1574.6 d	1752.6 c
P value	<0.0001	<0.0001	<0.0001	0.0051	<0.0001	<0.0001
Treatment	Intensity					
	2003	2004	2005	2003	2004	2005
	2003	2004	2005	2003	2004	2005
Control	21.83 a	19.79 b	17.77 c	21.83 a	19.79 b	17.77 c
100ET/ $K_c = 0.75$	20.07 c	23.25 b	19.11 b	20.07 c	23.25 b	19.11 b
100ET/ $K_c = 0.5$ – 0.8	21.19 b	20.56 b	20.31 a	21.19 b	20.56 b	20.31 a
150ET/ $K_c = 0.75$	18.33 d	25.23 ab	19.53 ab	18.33 d	25.23 ab	19.53 ab
150ET/ $K_c = 0.5$ – 0.8	21.84 b	28.57 a	19.41 b	21.84 b	28.57 a	19.41 b
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Treatment	Hue					
	2003	2004	2005	2003	2004	2005
	2003	2004	2005	2003	2004	2005
Control	0.58 d	0.55 c	0.59 b	0.58 d	0.55 c	0.59 b
100ET/ $K_c = 0.75$	0.74 b	0.59 a	0.67 a	0.74 b	0.59 a	0.67 a
100ET/ $K_c = 0.5$ – 0.8	0.59 d	0.56 abc	0.60 b	0.59 d	0.56 abc	0.60 b
150ET/ $K_c = 0.75$	0.95 a	0.58 ab	0.66 a	0.95 a	0.58 ab	0.66 a
150ET/ $K_c = 0.5$ – 0.8	0.64 c	0.53 c	0.71 a	0.64 c	0.53 c	0.71 a
P value	<0.0001	0.0202	<0.0001	<0.0001	0.0202	<0.0001

^a1 mg·L⁻¹ = 1 ppm.

^bMeans followed by different letters are significant at $P \leq 0.05$ via Duncan's multiple range test.

sites in 2005. Concentrations total phenols from the Beamsville site were higher than those from the Virgil site. Overall, total phenols were highest in all irrigated treatments in the 2005 season at both sites, and were higher in some irrigated treatments in 2003, but in 2004, the phenols were generally higher in nonirrigated treatments compared with irrigated vines at both sites. This seemed counterintuitive because the hot dry weather in 2003 and 2005 resulted in lower vine size and higher cluster exposure in nonirrigated vines, whereas in 2004, the nonirrigated vines had higher vegetative growth and more fruit shade. Total phenol concentrations from the Beamsville site were substantially higher than those from the Virgil site in the three seasons; this could be due to soil differences between the two sites.

Aroma compounds

METHYL ANTHRANILATE. MA increased in most irrigated treatments in the three growing seasons at both sites (Table 5). Specifically, at the Virgil site, four of four irrigation treatments exceeded the nonirrigated treatment in 2003, 2004, and 2005. The 150 ET treatments typically resulted in the highest MA. At the Beamsville site, three of four irrigation treatments exceeded the nonirrigated treatment in 2003, 2004, and 2005. Again, the 150ET treatments had the highest MA values in the 2004 and 2005 seasons. In general, MA concentration tended to be lower in the nonirrigated treatments, and were highest in the irrigated treatments in all three growing seasons at both sites. In a prior study, the lowest MA concentrations generally occurred in the nonirrigated treatments in 'Concord' and 'Niagara' (Reynolds et al., 2005a). In this study, the MA in 2004 was higher compared with 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, particularly monoterpenes (McCarthy and Coombe, 1985); however, this response was primarily due to reduction in berry volume (i.e., a concentration effect).

Table 5. Impacts of irrigation treatments on methyl anthranilate and total volatile esters of 'Sovereign Coronation' table grapes in 2003–05 at Virgil and Beamsville, ON, Canada. Treatments were not irrigated (control); 100% reference evapotranspiration [ET_0 (100ET)] with a fixed crop coefficient ($K_c = 0.75$) or a variable one ($K_c = 0.5-0.8$); 150% ET_0 (150ET) with a fixed or variable K_c value. Boldfaced data indicate those values significantly different from the nonirrigated control, Dunnett's t test; those boldfaced and underlined are significantly less than the control.

Treatment	Virgil, ON						Beamsville, ON					
	Methyl anthranilate (mg·L ⁻¹) ^a			Total volatile esters (mg·L ⁻¹)			Methyl anthranilate (mg·L ⁻¹)			Total volatile esters (mg·L ⁻¹)		
	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
Control	0.26 c ^y	0.47 d	0.27 d	34.54 b	30.18 d	30.50 c	0.32 c	0.45 d	0.26 c	30.44 b	28.87 e	31.10 b
100ET/ $K_c = 0.75$	0.28 a	0.48 c	0.29 c	37.57 a	31.10 c	32.50 c	0.39 a	0.45 d	0.27 c	32.54 a	29.89 d	32.51 b
100ET/ $K_c = 0.5-0.8$	0.26 b	0.50 b	0.30 c	35.26 b	31.74 c	34.30 b	0.36 b	0.31 b	0.31 b	31.44 ab	31.17 c	34.12 ab
150ET/ $K_c = 0.75$	0.26 b	0.53 a	0.31 b	35.96 ab	33.80 b	34.60 b	0.35 b	0.49 b	0.33 a	26.65 c	32.47 b	35.79 a
150ET/ $K_c = 0.5-0.8$	0.26 a	0.53 a	0.33 a	37.48 a	34.88 a	36.60 a	0.32 c	0.53 a	0.35 a	27.70 c	34.17 a	36.26 a
P value	<0.0001	<0.0001	<0.0001	<0.0001	0.0066	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^a1 mg·L⁻¹ = 1 ppm.

^yMeans followed by different letters are significant at $P \leq 0.05$ via Duncan's multiple range test.

TOTAL VOLATILE ESTERS. TVE were generally higher in response to irrigation in 2004 and 2005 at the Virgil site (Table 5). This trend occurred at the Beamsville site in the 2004 and 2005 seasons where the irrigated treatments had the highest TVE values, whereas in 2003, the nonirrigated treatment and 150ET/0.5–0.8 treatments had the lowest TVE values. The fact that TVE were higher in irrigated treatments over the three seasons at the Virgil site, and in 2 of 3 years at the Beamsville site suggests that mild water stress might reduce the berry's capacity to synthesize MA and other volatile esters. Those treatments with the highest yields and berry weight also produced the highest MA and TVE concentrations. This again suggests that minimizing water stress leads to enhanced MA and TVE accumulation.

RELATIONSHIPS BETWEEN WATER STATUS AND FRUIT COMPOSITION VARIABLES. Some cursory analysis using linear regression was attempted to elucidate possible relationships between soil and vine water status and key berry composition variables. Possible linear relationships among three water status variables [E, leaf ψ , and soil moisture (data from the final sampling dates)] and four berry composition variables (berry weight, soluble solids, MA, and TVE) were explored for each of the two sites for all three seasons. At the Beamsville site, relationships involving soluble solids were weak, with R^2 values <0.1 (data not shown). Relationships involving berry weight were likewise weak, although a relatively strong relationship [$R^2 = 0.31$ (data not shown)] existed between Ts rate and berry weight. MA was weakly related to soil moisture [$R^2 = 0.24$ (data not shown)] and weakly and inversely related with Ts [$R^2 = 0.31$ (data not shown)]. TVE followed opposite trends to MA in its relationships with soil moisture, ψ , and E, with R^2 values of –0.27, 0.18, and 0.28, respectively (data not shown).

Data from the Virgil site underscores the site-specific nature of the water status versus berry composition relationships. Soluble solids were related to leaf ψ on the final sampling date [$R^2 = 0.89$ (Fig. 6A)], suggesting strongly that low vine water status reduced soluble solids accumulation. A positive relationship between Ts

and soluble solids [$R^2 = 0.78$ (Fig. 6B)] suggested the same, and their distribution also suggested that Ts rates needed to exceed a threshold of about 14 $\mu\text{g}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ before increases in soluble solids could occur. Leaf ψ also displayed a strong linear relationship with berry weight [$R^2 = 0.89$ (Fig. 6C)], again suggesting strongly that low vine water status decreased berry weight. Ts rate and berry weight were also positively related [$R^2 = 0.75$ (Fig. 6D)], and, as with soluble solids, the bimodal distribution in the data suggested that about a 14 $\mu\text{g}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ threshold needed to be exceeded before increases in berry weight could occur. MA and water status variables were not linearly related and had R^2 values that were all <0.1 [e.g., leaf ψ (Fig. 6E)]. However, an apparent strong relationship existed between soil moisture and TVE [$R^2 = 0.76$ (Fig. 6F)].

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 (Virgil) and not the other; this may have been due to the much larger canopy volume at the Virgil site, which would have been more susceptible to low water status. It was also worthy of note that low water status, as measured by leaf ψ , was associated with lower soluble solids at the Virgil site. Increased soluble solids were clearly associated with increases in Ts rate at that site also, while berry weight and Ts were positively correlated at both sites. Of particular interest were the relationships between MA and TVE versus soil moisture and Ts rate at the Virgil site. Essentially, these were mirror images of each other; MA was positively correlated with soil moisture and inversely with Ts rate, while TVE showed opposite trends in relation to these variables. Increased MA concentration in 'Concord' and 'Niagara' was linked in one season to low soil and vine water status (Reynolds et al., 2005a); hence, these patterns in 'Sovereign Coronation' are somewhat contradictory to previous literature. However, the inverse relationship between MA and Ts rate

Fig. 6. Relationships between vine water status and berry composition variables of 'Sovereign Coronation' grapes at Virgil, ON, Canada in 2003 to 2005. Treatments were not irrigated (control); 100% reference evapotranspiration (ET_o) with a fixed ($K_c = 0.75$; 100/0.75) or variable crop coefficient ($K_c = 0.5-0.8$; 100/VAR); 150% ET_o with a fixed (150/0.75) or variable K_c value (150/VAR). Leaf water potential versus soluble solids (A); transpiration rate versus soluble solids (B); leaf water potential versus berry weight (C); transpiration rate versus berry weight (D); leaf water potential versus methyl anthranilate (E); soil moisture versus total volatile esters (F); 1 bar = 0.1 MPa, $1 \mu\text{g}\cdot\text{cm}^{-2} \cdot 2.2757 \times 10^{-7}$ oz/inch² (H_2O = water), 1 g = 0.0353 oz, $1 \text{ mg}\cdot\text{L}^{-1} = 1 \text{ ppm}$.

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 increasing Ts rate. This observation is more in accordance with Reynolds et al. (2006) who

observed that early and midseason moisture stress reduced concentration of monoterpenes in 'Gewürztraminer' (*V. vinifera*) berries.

Conclusions

This study has shown potential benefits of irrigation and its

magnitude of impact in cool climate regions such as Niagara. The FAO Penman-Monteith equation provided a means to determine ET_o . The van der Gulik equation (van der Gulik and Eng, 1987) may have overestimated irrigation needs early in the season by using a fixed K_c of 0.75, particularly

after major precipitation events. As canopy development was complete and no further rain events were recorded, it was clear that the crop coefficient used by the van der Gulik equation was in fact adequate and nearly equal to using an increasing crop coefficient as the season progressed. It is noteworthy, however, that the relatively small differences between the four irrigation treatments (whose ET_c values ranged from 50 to 112.5) suggest that the degree of intended precision used in this trial for the calculation of water volumes might not have been necessary. The use of soil moisture, leaf ψ , and T_s measurements nonetheless validated the ET -based calculations of water requirements. However, the use of the soil moisture sensor or other instruments that measure soil moisture at shallow depths is not recommended, and may in fact underestimate the true soil moisture level.

Irrigation reduced potential water stress in 'Sovereign Coronation' vines during generally dry seasons such as 2003 and 2005. The irrigated treatments had higher T_s rates, leaf ψ , and soil moisture values. Increased water led to increased yield (due largely to higher berry weights) and higher vine size. The larger berries (always desirable in table grapes) in irrigated treatments did not result in lower soluble solids. The TA values in the irrigated treatments were lower in 2004 and 2005 at both sites. Berry pH increased in irrigated treatments in 2005 but decreased in the 2003 and 2004 seasons. Among secondary metabolites, color intensity values tended to be higher in irrigated treatments versus the nonirrigated treatments. Total anthocyanins and phenols increased with irrigation in one season, but in 2003 and 2004, the anthocyanins and total phenols were often highest in the nonirrigated treatments. Methyl anthranilate and TVE concentrations were very sensitive to vine water status, and irrigation increased MA and TVE, suggesting that minimized water stress and larger berries led to enhanced MA and ester synthesis. As expected, nonirrigated treatments generally had lower T_s rates, soil moisture values, and leaf ψ measurements. Although water status data for nonirrigated treatments on some

sampling dates did not always meet the generally accepted parameters for being classified as water stressed ($\psi < -12$ bars), they were still much lower than the irrigated treatments.

Calculation of irrigation needs is relatively easy, particularly if the ET_o value can be obtained from state or provincial websites (Reynolds, 2008). Once obtained, it needs merely to be multiplied by a K_c value, a soil water storage factor, and plant area to calculate a volume per vine. This volume figure can be converted to a value in irrigation hours based upon the dripper output and the ratio of dripper and vine spacing.

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