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Irrigation Management in Ontario: How Much is Enough?

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Vineyards in the East and Midwest have mostly not been irrigated because of a lack of a perceived cost:benefit ratio. However, several years of drought in Ontario, New York, and elsewhere have resulted in problems including low yields, poor shoot growth (zinc and boron deficiencies), pest problems (erineum mite and European spider mite), and enological issues (low sugar; low pH and potassium; atypical aging). These years of drought in the Niagara Peninsula caused many growers and wineries to examine the feasibility of irrigation for grapes. Many vineyard blocks displayed drought stress symptoms between 1997-99, 2001-02, and 2005. In 2007, we were faced with another serious drought, with precipitation levels reported to be 46% below average between early June and early September. Drought stress and actual drought injury were widespread.

In parts of the East, some wines from Great Lakes vineyard blocks have displayed flavors of atypical aging (ATA) over the past few years, which are consistent with drought and nitrogen stress. ATA has expressed itself mainly in aromatic varieties such as Riesling, Gewürztraminer, and Chardonnay. Reductions in yield and vine vigor have also been widely reported. Consequently, there is a great need to do research on irrigation and fertigation, and to develop affordable and efficacious technologies.

Irrigation may be a way of overcoming some or all of these problems, but there is a need to know how much water to add, and how the irrigation should be timed. When I get into conversations with grape growers, the topic invariably leads to “How much water should I apply?” The second most common question is usually, “When should I start irrigating and when should I stop?” Both questions are fundamental, but not necessarily ones that will be the same every year and for every grower. Another very common question is, “Do these droughts have anything to do with global warming and climate change?” I don’t know the answer to that question, but one thing is clear: most climate change models describe reductions in precipitation along with increases in mean annual temperature, which certainly suggest more frequent droughts. These questions and others notwithstanding, now that a large proportion of the winegrape acreage is planted to premium varieties, the wine industry needs to address the potential for increasing winegrape yield and quality, and at the same time, sales.

A lot of attention has been given to "deficit irrigation." Deficit irrigation is usually defined as withholding irrigation water followed by re-watering to maintain soil water level above the physiological wilting point but considerably below field capacity (Caspari et al. 1994). Another definition is adding water at some volume below the replacement evapotranspiration (ET). The concept of imposing deficit irrigation strategies to conserve water and control vegetative growth was first explored for peaches (Chalmers et al. 1981) and was subsequently evaluated on apples (Ebel et al. 1995), pears (Chalmers et al. 1986), and Asian pears (Caspari et al. 1994). Vigorous grapevines produce dense, shaded canopies that may reduce winegrape quality (Smart et al. 1985). A mild water stress imposed through irrigation deficits (Caspari et al. 1997; Matthews and Anderson 1988, 1989; Matthews et al. 1987; Trought and Naylor 1988) may reduce vine vigor and reduce competition for carbohydrates by the growing tips, and is likely to increase the quality of the fruit produced. Specifically, there is some evidence that reducing irrigation (but not water *stress*) may lead to increased concentration of flavor compounds in the fruit (McCarthy 1986; McCarthy and Coombe 1985; McCarthy et al. 1987). In fact, some work in British Columbia specifically showed that irrigation deficits imposed early in the season could result in reduced flavor compounds (Reynolds et al. 2006).

As the winegrape industry expands in the Northeast at a time when water shortages are becoming critical, more definitive information is needed on the response of premium winegrapes to imposed irrigation deficits and to soils of low moisture-holding capacity. We have conducted a series of experiments on *Vitis labrusca* (Concord and Niagara), table grapes (Sovereign Coronation), French-American hybrids (Baco noir), and several *V. vinifera* (Chardonnay, Sauvignon blanc, Cabernet Sauvignon) to investigate the impact of different durations of water stress upon vine performance, fruit composition, and water relations of field-grown Chardonnay grapevines.

Irrigation – How Much is Enough?

Calculating evapotranspiration (ET)

In order to understand irrigation and plant water relations, it helps to begin with a simple model of inputs and losses to an agricultural system. Water inputs include rainfall (and snow melt), irrigation, and capillarity from underground aquifers. Losses from the system include percolation through the soil profile, transpiration, and evaporation from the soil surface. The losses due to evaporation and transpiration are referred to as evapotranspiration (ET). Mathematically it can be expressed as:

Rainfall + irrigation - runoff - ΔPW = percolation + ETo

where ΔPW is the change in volume of water stored in the soil during a specified time period.

ET is expressed in terms of mm over a specific time period, whether that is per day or per year. It varies with weather conditions; ET is at its maximum in midsummer where day length (sunshine hours) is at its maximum, relative humidity is low, and temperatures are highest. Some regions have actual evaporation pans that are used to estimate ET (Irmak and Haman 2003). Other regions employ various equations, which include those of Penman (1948), Kohler, Nordensen, and Fox (Kohler et al. 1955), Christiansen (1968), Priestley and Taylor (1972), Linacre (1977), and finally the Penman-Monteith (Allen et al. 1998). This latter equation makes use of several meteorological variables and the decision was made to use this equation to calculate reference ET (ET_o) (see Figure 1 below). However, most of the states in the U.S. and the Canadian provinces now provide ET_0 values on state and provincial websites, and so calculating ET_0 values need not be so onerous and time-consuming. In this area, the Weather Innovations Network (http://www.weatherinnovations.com/ET.cfm) provides a weekly-updated map that shows ET_o values around the province of Ontario, calculated using the Priestly-Taylor equation. So, for sake of argument, let's say that your peak ET_o value is 0.26 inches (6.6 mm) per day. We'll follow this ET_o value through the calculations that follow and come up with how much water to apply to a vineyard.

$$ET_0\ (\text{mm/day}) = \frac{[0.408\Delta(R_n - G + \frac{900}{T_{ave} + 273}\mu_2(e_s - e_a)]}{\Delta + \gamma(1 + 0.34\mu_2)} \qquad \text{Equation 1}$$

Variables:
ET_0 = 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 vapor pressure [kPa],
e_a = actual vapor pressure deficit [kPa],
e_s - e_a = saturation vapor pressure deficit [kPa],
Δ = slope vapor pressure curve [kPa °C^{-1}],
γ = psychrometric constant [kPa °C^{-1}].

Figure 1. The Penman-Monteith equation (from Allen et al. 1998).

Using a crop coefficient

ET_o is based upon losses from a grass cover crop that covers 100% of the surface of a given area. In the case of grapes, they are in rows that are about 2.5 m (8 feet) apart, and consequently much of the surface of the soil is not occupied by canopy. We need to account for the fact that grapes are trellised and may occupy up to 1.8 to 2 m (about 6 feet) of trellis space, which if laid flat would cover approximately 75% of the soil surface. This is the basis for use of a crop coefficient (K_c). If irrigation is being applied to a vineyard containing a full trellis, a K_c of 0.75 to 0.8 is usually appropriate. If irrigation is applied during canopy development, the volume of canopy must be estimated as accurately as possible. One method of doing so is to measure the length of the shadow cast by the vine canopy, and divide this by the row width. The K_c is thereafter multiplied by the ET_0 to calculate crop evapotranspiration (ET_c). This is the value that we use to calculate replacement water volume. If you use our original ET_o value of 6.6 mm and a 0.75 K_c, then our ET_c would be 6.6 x 0.75 or 4.95 mm (0.19 inches) of replacement water daily.

Calculation of water volume requirements per vine based on ET, K_c, soil water storage, and vine area (from Van der Gulik 1987)

To calculate the number of liters per vine per day, a simple engineering equation based on a number of multiplications, can be used:

$$\textbf{Liters/vine/day} = \mathbf{0.623 \times 3.785 \times ET_0 \times S \times A \times K} \qquad \text{Equation 2}$$

where $0.623 = \dfrac{27.152\text{USgallons/ acre} - \text{inch}}{43{,}560\text{feet}^2 \text{ / acre}}$

3.785 = conversion from U.S. gallons to liters

ET_0 = reference evapotranspiration

S = soil water storage factor

A = plant area

K = crop coefficient factor

The factors in this equation can be restated substituting ET_0 for ET_o + K (K_c):

ET_c (0.19 inches)

Conversion factor from gallons to liters (3.785)

U.S. gal per acre-inch/sq ft per acre (0.623)

Soil water storage factor (0.75 for vinifera grapes)

Plant area in sq. ft. for vinifera based on 4 x 8 ft. (32)

Thus:

0.19 x 3.785 x 0.623 x 0.75 x 32 = 10.75 liters per vine per day.

Normally, we assume that our clay loam soils have enough storage capacity to allow weekly irrigations. Therefore:

10.75 L/day x 7 = 75.25 liters per vine per week (V_w).

Next: Subtract the volume of rain (P) that fell during the previous week. An adjusted value (P_{adj}) is obtained by subtracting the likely runoff amount of 12 mm from P. If, for example, half an inch (12.7 mm) of rain fell during the week prior to the irrigation day, the P_{adj} value would be 12.7 mm - 12 = 0.7 mm. The P_{adj} value may then be converted to liters by the following calculation:

P_{adj} in liters = P_{adj} /25.4 mm x 122.530 L/1200 vines

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

In this example, we have a P_{adj} value as follows:

P_{adj} = (0.7 mm/25.4 mm) x (122,530 L per acre-inch/1200 vines per acre = 2.8 L per vine/week

By subtracting P_{adj} from V_w to arrive at a final volume per vine to apply (V_f):

V_f = 75.25 L - 2.8 L = 72.45 L per vine per week.

The final step is to convert volume to time in hours. You know that the final volume per week to apply is 72.45 L per vine, and that your irrigation system delivers 4 L/hour from drippers spread 1 m (40 inches) apart, and the vines are spaced 1.2 m (4 feet), then the time required is:

72.45 L/4 L per hour x 0.83 = 15 hours

where 0.83 is the ratio between dripper spacing (1.01 m or 40 inches) and vine spacing (1.8 m or 48 inches).

Voila! You have just calculated how much to irrigate!

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Measuring Soil and Plant Water

Soil moisture

Several instruments can be used to measure soil moisture. The question then becomes how can these data be used? A **Theta Probe** (Delta-T Devices, UK) was initially used to monitor soil moisture levels in our juice grape, table grape, and Chardonnay trials. The Theta Probe consists of a 1.5-m rod to which three 10-cm steel probes are affixed at one end. The probes are inserted into the ground, an electrical impulse is passed down the probes into the soil and then returns to its source; the rate of return of the impulse is proportional to the water content of the soil. Readings are typically taken prior to each weekly irrigation, and at the same times for the control treatments, adjacent to each data vine.

The Theta Probe works using the same principle as **time domain reflectometry (TDR)**, whereby once again an electrical impulse is passed down a stainless steel rod, then "jumps" across to a parallel rod and back up to the source. The time required for this to take place and the magnitude of the returning impulse are inversely proportional to the soil water content. The shortcoming is the length of the probes; at 10 cm, they measure only the surface moisture and may not tell you much about the soil environment further below. We now use a portable TDR with both 12 cm and 20 cm probes, and the results are much more reliable. Both the Theta Probe and TDR express their data in % volumetric soil moisture.

Another tool we have recently acquired is the **Profile Probe** (also Delta-T Devices, Burwell, Cambridge, UK; www.delta-t.co.uk). This employs a series of 5 cm diameter Teflon tubes that are inserted into the soil in the vine rootzone. The actual probe is thereafter inserted and soil moisture values are generated over a depth of 1 meter. Data are expressed as % volumetric soil moisture.

Soil moisture data are of no use unless you know the field capacity and the wilting point of the soil. Without these values, you have no benchmarks and soil moisture data are of very little practical use. As a general point of reference, heavy clay soils such as the Jeddo, Morley, and Toledo series in the Niagara Peninsula have wilting points of about 25% soil water by volume, while the clay loams such as the widespread Chinguacousy series have wilting points around 13% soil water (Kingston and Presant 1989).

Transpiration

Transpiration measurements are typically taken on exposed, recently-expanded leaves during the 10:00 a.m. to 4:00 p.m. time period. In our research plots, these data are collected once a week on an hourly basis throughout the day using a **steady-state porometer**. The porometer actually measures either stomatal conductance or stomatal resistance and then converts these values to transpiration. A porometer is mainly a research tool and has as shortcomings its expense, a lack of robustness for field use, and difficulty in interpretation of the results.

Pressure bomb

Pressure bombs are widely used in the industry, particularly in California and Australia. The bomb consists of a thick-walled steel chamber into which a leaf is inserted, with its petiole exposed. It is held in place with a neoprene grommet. As the chamber is pressurized, water is gradually forced out of the leaf and this collects at the base of the cut petiole. The pressure at which the water droplets are first noticed is equal to the leaf water potential (Ψ), which is actually the tension by which water is held inside the leaf. Mature, fully-exposed leaves are sampled at midday on cloudless days. We typically cut the petiole with a sharp razor blade and immediately bag it, after which the Ψ reading is made. Variations to this procedure include pre-dawn Ψ (Williams 2001) and stem (petiole) Ψ (Chôné et al. 2001). A pre-dawn reading tends to be higher (i.e. less negative) than a midday sampling, while a stem Ψ reading is generally lower (more negative).

Some Case Studies from Our Research Trials

General objectives

The overall goals of these projects were to assess irrigation treatments in juice grape, table grape and premium winegrape vineyards with the ultimate goal of improving yield, fruit composition and, where appropriate, wine quality.

General irrigation setup

In the case of the juice grapes, we used a microporous plastic "ooze-tape" that was buried about 20 cm (8 inches) below the surface. In the case of our table grape and winegrape trials, we used RAM plastic irrigation tubing with in-line drippers that were installed every 100 cm (40 inches). Water was applied weekly as prescribed through individual valves installed at the top of each row.

The trials on table grapes and winegrapes were conducted at Lambert Farms, Niagara-on-the-Lake, Ontario. Initially, an 8-year-old block of Chardonnay was chosen for study. This section was divided into five, five-row blocks, with the outside row used as a buffer row. We assigned five treatments randomly to each block, and chose nine equally-distributed vines for data collection in each row. We tested various timings of irrigation, including full season irrigation, plus water deficits imposed at fruit set, lag phase of berry growth, and véraison. Treatments therefore were: non-irrigated control; early deficit irrigation (reduced irrigation at post-set); midseason deficit irrigation (reduced irrigation at lag phase of berry growth); late season deficit irrigation (reduced irrigation at véraison); and full season irrigation. Our objective was to impose mild water stress at varying intervals and durations throughout the season. In an attempt to quantify the impact of this water stress, data was collected on yield components, fruit composition, and vine vigor, as well as measurements of soil water, grapevine transpiration, and soil and vine nutrient levels. We made wines from the various irrigation treatments and analyzed these chemically and sensorially.

Concord and Niagara juice grapes

A study was conducted between 1998 and 2002 to investigate the impact of different durations of irrigation and fertigation upon vine performance, fruit composition, and water relations of Concord and Niagara (*Vitis labrusca*) grapes in the Niagara Peninsula in Ontario, and to quantify the degree of water stress that vineyards in the region typically experience (Reynolds et al. 2005). The six Concord treatments were a non-irrigated control, irrigation from budburst to véraison, and four fertigation treatments which applied 80 kg of nitrogen per hectare as urea. The nine Niagara treatments were a non-irrigated control, two irrigated treatments (ceasing at véraison and harvest, respectively) and six fertigation treatments of various durations. The FAO Penman-Monteith evapotranspiration formula was used in the final season to calculate water budgets and schedule irrigations. Transpiration rate and soil moisture data suggested that water stress was present in these vineyard blocks in three out of the five years of the study. The small transpiration differences between control and irrigated or fertigated treatments may have been due to early season irrigation increases in canopy size that led to later season water stress. Irrigation and fertigation led to enhanced berry set, larger berry size, increased vine size and small increases in yield. Slight yield increases (ca. 10% in Concord; 29% in Niagara) in irrigated and fertigated treatments were attributable to increased cluster numbers, cluster weights, and berry weights. In most seasons, yield increases were accompanied by small decreases in soluble solids (1.5 to 3°Brix) and methyl anthranilate concentrations. Timing of fertilizer application did not play a major role in any of these attributes.

Sovereign Coronation table grapes

Five irrigation treatments [non-irrigated control plus four treatments based on combinations of two evapotranspiration (ET_0) values and two crop coefficients (K_c)] were evaluated on Sovereign Coronation table grapes (2003-05) at two sites [Hipple Farms (Beamsville); and Lambert Vineyards

(Niagara-on-the-Lake)] in the Niagara Peninsula of Ontario (Reynolds et al. 2008). The modified Penman-Monteith equation was used to calculate ET_0 using relative humidity, windspeed, solar radiation, and temperature data from the Ontario Weather Network, and the ET_0 values (either 100 or 150%; ET100 or ET150) were multiplied by one of two Kc values (fixed at 0.75 or 0.5 to 0.8 based upon increasing canopy volume) to calculate volume of irrigation water and to define the four irrigated treatments. Irrigation increased transpiration rate and soil moisture; the non-irrigated control showed consistently lower transpiration rate and soil moisture over the 3 seasons. Leaf water potential (ψ) was also lowest throughout the 3 seasons for non-irrigated treatments. Vine water status measurements confirmed that irrigation was required for the 2003 and 2005 summers due to dry weather. Irrigation increased yield and its various components in 2003 and 2005; berry weights were higher in irrigated treatments at both sites. Berry weight was the main factor leading to these increased yields, as inconsistent results were noted for some yield variables. Brix was highest in irrigated treatments. Titratable acidity (TA), pH, anthocyanins and phenols were highest in controls in 2003 and 2004, but highest in irrigated treatments in 2005. Methyl anthranilate (MA) and total volatile esters (TVE) were highest in the ET150 treatments. Conclusions are: 1. Irrigation scheduling using the Penman-Monteith equation was successful in calculating vineyard water needs; 2. Irrigation (ET150 treatments in particular) effectively reduced water stress and improved yield and fruit composition.

Chardonnay

Five irrigation treatments (non-irrigated control; irrigation cut-offs imposed postbloom, lag phase, and véraison; full season irrigation) were evaluated in an Ontario Chardonnay vineyard over a 4-year period (2001-04). The Penman-Monteith ET formula was used to calculate water budgets and schedule irrigations. Transpiration rate, midday leaf water potential, and soil moisture data suggested that the control and early cut-off treatments were frequently under low water status, despite ample precipitation in 2 of 4 seasons. The full season irrigation treatment increased yield by 18% (2001) and 19% (2002) over the control due primarily to increased berry weight. Soluble solids were increased by irrigation, and the full season irrigation treatment showed similar or higher Brix than all other treatments in 2 of 4 years. Berry titratable acidity (TA) and pH also fell within acceptable levels for all five treatments, although TA was slightly higher in irrigated treatments in 2 of 4 years. Wines from irrigated treatments had greater intensities of apple, citrus, and floral aromas and flavors, as well as lower levels of earthy aroma and flavor. The wines from irrigated treatments also were not judged as “different” when subjected to the ATA test, whereby samples of the wines $\pm$

ascorbic acid are heated for 48 hours and then evaluated sensorially for differences (if different, the wines are considered likely to develop ATA). These results strongly suggest that irrigation is a viable option for winegrape vineyards in Ontario and the northeastern United States, with potential for simultaneous increases in yield, soluble solids, and desirable wine sensory attributes.

Syrah in California

Despite widespread irrigation use, California continues to seek innovative technologies for accurately calculating vineyard water needs. Syrah/110R vines in the Dunnigan Hills were spaced 1.8 x 2.7 m (vine x row), trained to 1-m high bilateral cordons and pruned to 19 nodes per m row; vine size was 0.8 kg/m. Treatments were based upon evapotranspiration (ET), and crop coefficients (Kc) estimated from canopy volume. Six treatment combinations of three ET values (100%, 50%, 25%) and two Kc values [0.6 and 0.2-0.8 ("variable")] were imposed in a randomized block containing four replicates and 12 equally-spaced vines per three-row treatment replicate. Treatment imposition began at fruit set and continued until one week before harvest (August 25, 2004; September 20, 2005). Midday leaf water potentials (Ψ) were lowest in the 25ET/variable vines, and were < -15 bars on several dates. Petiole conductance (measured by a Phytogram platinum probe inserted into the petiole) followed the same pattern as Ψ, and therefore this technology has potential for allowing vineyard managers to monitor vine water status from a remote location. Irrigation had no effects on most yield components. Berry weight was highest in the 100ET/variable and lowest in the 25ET treatments. Soluble solids were highest in 50ET and 25ET treatments in 2004 (>25 Brix), and lowest in the 100ET berries; in 2005 the 25ET treatments were lowest (<25 Brix). Titratable acidity (TA) was lowest in 25ET and 50ET/variable treatments in 2004; 50/0.6 berries were highest (5.9 g/L). pH was highest in 2004 in 25ET/0.6 (4.19) and lowest in 100ET/variable and 50ET/0.6 berries. Few irrigation effects were observed on TA and pH in 2005. Total anthocyanins were unaffected in 2004 but 50/variable and 25/0.6 had lowest anthocyanins in 2005. A520 and color intensity (A420 + A520) were highest in 25ET treatments in 2004 and were lowest in the 100ET treatments; the trend was reversed in 2005. Phenols were highest in both 25ET treatments in 2004 but 100ET treatments had highest phenols in 2005. Sensorially, 25ET treatments diminished red fruit aroma/flavor without impacting intensity of any other fruit components, and had least vegetal and most lavender and chocolate aromas, and retronasally, they had most dark fruit, anise, alcohol/heat, viscosity, and length. This trial ran from 2004 to 2008 inclusive.

Ongoing trials initiated 2005-06

An irrigation trial was initiated on Baco noir in 2005 and was terminated in 2008, with 3 seasons of data collected. There were 10 treatments: control (non-irrigated), plus three times of initiation (fruit set, lag phase and véraison) factorialized with three ET values (25, 50 and 100%). Data are still being compiled and analyzed, but preliminary results show a clear effect of ET on both soil moisture and transpiration. We collected data from 2005 to 2007 inclusive. A related Chardonnay trial ran from 2005 to 2008 inclusive, with 4 seasons of data collected. That trial involved seven treatments: control (non-irrigated), plus two times of initiation (fruit set and véraison) factorialized with three ET values (25, 50 and 100%).

Two other trials were initiated in 2006, one on Sauvignon blanc and the other on Cabernet Sauvignon. Both are testing the efficacy of partial rootzone drying (PRD), or the ability to irrigate 50% of the rootzone of a perennial plant while the other remains dry, and in the process, transmits an abscisic acid signal to the shoots from the dry rootzone, which subsequently has physiological impacts such as reduced shoot growth The two trials consist of a non-irrigated control, two ET treatments (50 and 100%), and a PRD treatment. The Sauvignon blanc trial concluded in 2008 after 3 years of data collection. The Cabernet Sauvignon trial is intended to run longer than 3 years (2006-09 and beyond). As with the Baco noir trial, data are still being compiled and analyzed.

Conclusions and Grower Benefits

Increased revenues

We felt at the initiation of these projects that irrigation could result in increases in yield, coupled with an improvement in winegrape quality. We were fairly accurate in this prediction, since a full-season irrigation for Chardonnay in 2001 provided an 18% yield increase. We also predicted an increase in soluble solids; we only got a 2% increase, or 0.4 °Brix, but this still gave us an additional $25/ton.

Cost reductions

Grapes cost about CD $800/ton to grow in the Niagara Region, with at least 20% of these costs devoted to pruning. If we can reduce vine vigor by deficit irrigation, we should be able to save 15% of the pruning costs.

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