Transpiration of Grapevines in the Humid Northeastern United States

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Abstract: For irrigation design and scheduling, water use of crops is commonly estimated from grass reference evapotranspiration (ET_0) estimates multiplied by published crop coefficients (k_c). This method is assumed to stabilize k_c across climates because of the response of ET_0 to meteorological variables. However, the simple application of reference grass-based k_c models may not be accurate in a cool, humid climate, especially for sparse and tall crops where stomatal regulation is well-coupled to bulk air and sensible and latent heat exchanges may have a different dynamic than in grass. The aim of this work was to measure actual transpiration in a vineyard in the humid climate of New York and compare the results with the estimates obtained using the reference grass-based crop coefficient model. Measurements of water use in Concord grapevines (*Vitis labruscana* Bailey) were made with heat-balance sap-flow gauges calibrated against canopy gas exchange chambers. Daily ET_0 was estimated from meteorological data acquired by a nearby weather station. Daily transpiration rates per single vine ranged between 15 and 40 L day^{-1}, with hourly rate peaks of 4 L hr^{-1}. Water use declined during the hottest and driest part of the season, probably due to either water or heat stress. Results suggest that even in humid climates, grapevines might require irrigation occasionally. The reference grass-based k_c was inadequate to quantify the degree of coupling between stomatal regulation of transpiration and bulk air conditions, specifically vapor pressure deficit. Overall, results suggest the necessity of developing crop-specific models for water management.

Key words: vineyard, sap flow, crop coefficient, water use, *Vitis labruscana*

Water use is often estimated from the evapotranspiration (ET) of a well-known reference surface like grass and related to the crop of interest by means of specific crop coefficients (k_c) that are fractions of the reference value. Reference grass-based crop coefficients are intended to adjust water-use values for the differences between the reference surface and the crop of interest, such as species, physiology, stage of growth, structure of canopy, and training system (Allen et al. 1998). Despite its common use, the accuracy of this approach with discontinuous canopies like those in vineyards cannot be assumed. Reference grass does not represent correctly the unique atmospheric relationship of sparse and taller crops, particularly in latent and sensible heat exchanges. In general, transpiration in tall and sparse crops is controlled more by bulk air conditions than in the short and dense grass canopy, where water use is driven mainly by net radiation (McNaughton and Jarvis 1991). In this respect, reference grass-based crop coefficients lack sensitivity to the effects of bulk air conditions on transpiration. Their application on taller and sparse crops should be evaluated carefully, especially across climates (Annandale and Stockle 1994). These concerns are likely to be more critical in humid regions where the historical abundance of water has led to little research emphasis on the water use of various crops and irrigation management is often based on crop coefficients determined in arid climates.

In general, Concord vineyard (*Vitis labruscana* Bailey) grapegrowers have not used irrigation in the northeastern United States or Canada because precipitation is typically sufficient to support the crop. However, variability in rainfall can lead to drought periods of varying duration and intensity. This uncertainty, together with an emphasis by growers on increasing yields to reduce production cost per ton, has led to new interest in vineyard irrigation. Several techniques are currently available to measure or estimate water use in woody plants. Among them, sap-flow gauges are common (Wullschleger et al. 1998) and offer several advantages: direct measurement of the water stream through the plant (or smaller sections of the water pathway); continuous and long-term monitoring; no disruption of plant canopy or root environment; and automated calculation of transpiration rates. Three types of gauge are available: heat dissipation, heat balance, and heat pulse (Granier 1985, Sakuratani and Abe 1985, Smith and Allen 1996). All rely on the thermal dissipation prop-

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erties of water flowing through the stem to estimate transpiration. However, these methods are uncertain because of some difficult-to-prove assumptions used to convert measured variables to mass flow (Shackel et al. 1992, Clearwater et al. 1999, Grime and Sinclair 1999, Ferrara and Flore 2003). In addition, trunk core samples for anatomical analysis of the test plant stem may be needed to estimate mass flow from computed sap velocity; when that is not possible or is undesirable there is further uncertainty in sap-flow estimates. Plant-specific characteristics such as very high flow velocities, variable stem structure, and wide diameter trunks can introduce additional errors (Ham and Heilman 1990, Braun and Schmid 1999, Tarara and Ferguson 2001). It may be questionable to assume implicitly that sap-flow gauges are accurate on large plants in the field unless they are calibrated against an alternative technique or unless numerous probes are used to deal with plant variability and other technical difficulties. Direct calibration can be easily performed on potted plants by weighing, but in the case of large field-grown plants, it is only feasible with large lysimeters (Wullschleger et al. 1998, Williams et al. 2003a) or using the trunk excision method (Green and Clothier 1988), which, however, requires cutting of the plant at ground level and introduces artificial conditions.

Another approach to measure directly the transpiration rates of large field-grown plants is the use of whole-canopy gas exchange chambers with infrared gas analyzers (Corelli-Grappadelli and Magnanini 1993, Lakso et al. 1996, Poni et al. 1997). This method relies on a few verifiable assumptions, particularly about flow rates and the analysis of CO_2 concentrations, and therefore is less prone to systematic errors than sap-flow gauges. However, the chamber establishes an artificial environment around the plant, limiting the generalization of the results to undisturbed conditions.

In this work we applied a combined approach to estimate transpiration that also has been used successfully in studies of apple tree transpiration (Dragoni et al. 2005). The sap-flow technique was used to provide continuous estimates of grapevine transpiration, while canopy gas exchange chambers were used for a short period to provide a direct calibration of the sap-flow gauges, and then removed for undisturbed sap-flow measurements. The purpose of this work was to fill the lack of knowledge on grape water use in cool humid climates, such as New York, and to test the reliability of the reference grass-based crop coefficient model on a tall, discontinuous canopy in the same humid climate.

Materials and Methods

The experiments were performed at Cornell University, New York State Agricultural Experiment Station, Geneva (42N, 77W) in 2002. Measurements were collected from five-year-old own-rooted Concord grapevines. Rows were 2.74 m apart and oriented north-south. Vines were spaced at 2.44 m within the row, giving 1495 vines ha^{-1}. One-third of the length of each row was trained to Geneva double curtain (GDC) and two-thirds to single curtain (SC). Two trunks (average diam ≈20 mm) were trained per vine, each one supporting one-half of the canopy. In SC, each trunk extended for half of the space between vines, while in GDC, each trunk extended for the entire distance between vines, making extension in GDC twice that of SC on both vine and hectare bases. Ten half-vines (four GDC trunks and six SC trunks) were selected for uniformity of canopy within the training system.

Transpiration estimates. Sap flow in each half-vine canopy was estimated by gauges based on the heat-balance technique (Baker and Van Bavel 1987, Smith and Allen 1996). This method is suitable for small-diameter woody stems (such as <90 mm) (Steinberg et al. 1990). Heat-balance sap-flow gauges were built according to a U-shaped design (Senock and Ham 1993), with modification to accommodate the high rates of sap flow expected in mature Concord vines (Tarara and Ferguson 2001) (J. Tarara 2003, unpublished data). Specifically, temperature sensors were separated from the heating collar by ~5 cm to ensure thermal homogeneity across the stem at the location of the downstream thermocouples. A sap-flow gauge was mounted on one of the two main trunks of each selected vine, at a distance of 1.2 to 1.5 m aboveground to minimize temperature gradients from the soil. Before installation on the trunk, loose bark was carefully removed to reduce vine surface irregularities and facilitate heat diffusion. Temperature sensors were positioned over smooth internode tissue to ensure good stem-to-thermocouple contact. Stem diameters at gauge locations averaged 19.8 ± 1.0 mm. Thermal insulation (~5 cm thick) and reflecting material were applied around the gauges and extended to the soil surface, as recommended for woody stems (Gutiérrez et al. 1994). Gauges were left in place until the end of the experimental period. The change in heat storage in the portion of the stem heated by the gauges was assumed to be negligible, which is not always the case (Grime et al. 1995), but calibration of gauges against the gas exchange chambers corrected for errors from systematic violation of this assumption. Gauges were operated in constant power mode. Heat (≈02.5 W) was applied to the stem between 0300 and 2000 hr (LST) daily. The applied power was selected to maintain the difference in stem temperature between upstream and downstream thermocouples (T_{oi}) in a range from 0.5 to 4.0°C, during the day. As a result, T_{oi} was, on an average sunny day, between 1.0°C (highest flows) and 3.5°C (lowest flows); any measurements made when $T_{oi} < 0.5$°C were rejected. Heaters were turned off temporarily if T_{oi} exceeded 4°C. Raw measurements from gauges were acquired each minute and averaged hourly by a datalogger (CR10X, Campbell Scientific Inc., Logan, UT). The final data set extended from 11 July to 9 Sept 2002.

Gas exchange measurements. Transpiration rates obtained from the heat-balance system were calibrated against simultaneous measurements of half-vine gas exchange, using flow-through chambers on SC vines from 20 to 28 Aug 2002. Four SC vines were selected because of a limitation in the size of the canopy chambers (GDC vines extended twice the length of SC) and in the number of chambers that could be controlled simultaneously. The canopy chambers were built in-house and made with Mylar film (Dupont, Wilmington, DE), which is transparent in the infrared (IR)(>700 nm) and transmits ~90% PAR (400 to 700 nm). The canopy chambers were designed specifically to fit closely around the canopies of the test vines and were gathered and tied around the trunk (Figure 1). A fan-pipe system provided constant airflow through the chambers and was set to ensure complete turnover of air volume each minute. Air temperature inside each chamber was monitored using a shielded type-T thermocouple placed at the top of the canopy.

A data acquisition system based on a CIRAS–1 gas analyzer (PP Systems, Haverhill, MA) with a CR10X datalogger (Campbell Scientific) was used to detect and record differences in water vapor and carbon dioxide concentrations between inlet and outlet air streams from all four chambers. Measurements were sequentially recorded from each vine in the series. Data were acquired with a frequency of 10 Hz for 180 consecutive seconds, and three averages of 1 min each were stored. Data acquisition was then paused for 1 min to allow the gas flow to equilibrate to the new sample after switching between vines. Three consecutive 1-min averages acquired every 16 min constituted the final data set of 92 3-min values per day for each vine. Details on transpiration estimates using canopy these chambers have been published previously (Dragoni et al. 2005).

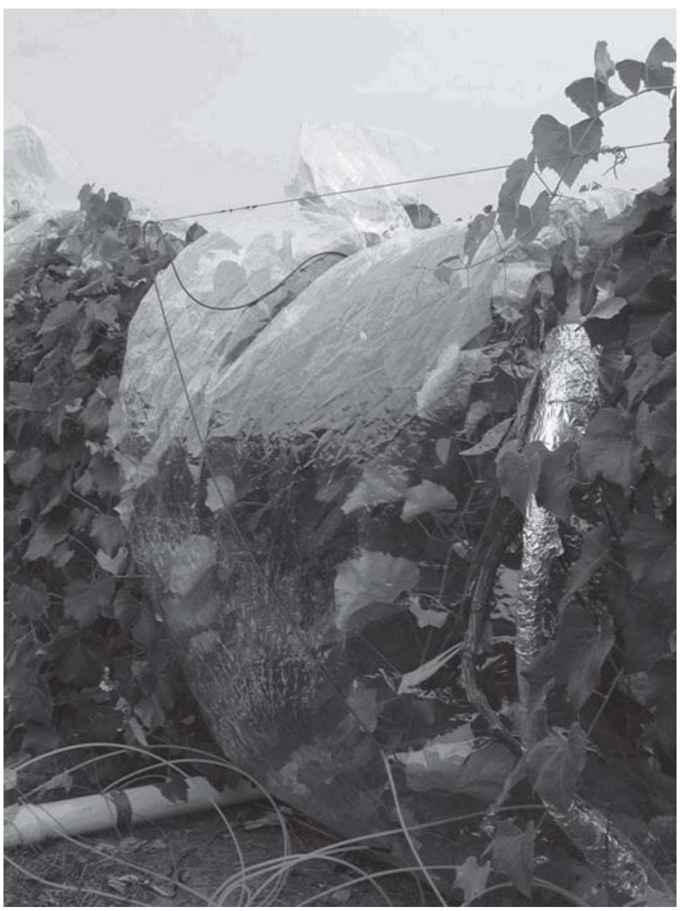

Figure 1 Whole-canopy gas exchange chamber system in grapevines. Air flows through the chamber via a fan-pipe system at the base of the chamber. The chambers are closed around the vine main trunk to exclude soil fluxes.

Because only four sap-flow gauges could be calibrated against gas exchange chambers, an indirect method was used to estimate transpiration rates for the other six experimental vines. Aggregated across the four SC vines used for the chamber calibration, T_{oi} explained 93% of the variability in the hourly estimates of calibrated transpiration rate per unit leaf area (Figure 2). A linear relationship was obtained by regressing the log-transform of chamber-estimated transpiration against T_{oi}. This regression equation was assumed to be valid for both SC and GDC vines, and thus it was used to estimate transpiration for the noncalibrated (i.e., GDC) vines. To extrapolate half-vine measurements to the whole vine, symmetry was assumed between the two canopy portions of the same vine and transpiration rate and leaf area were both doubled from the half-vine measurement.

Leaf area. To compare measurements of transpiration rates among vines on the basis of leaf area (LA), leaf area per vine was estimated at the end of the growing season. Shoot length was measured for all shoots on the experimental half-vines. Full canopy LA was estimated by means of an allometric relationship between leaf area and length of the shoots, obtained by direct measurement of LA (WinDIAS image analysis system, Delta-T Devices Ltd., Burwell, UK) from a selected sample of shoots. Broken shoots (~30% of total) were assigned to a total shoot

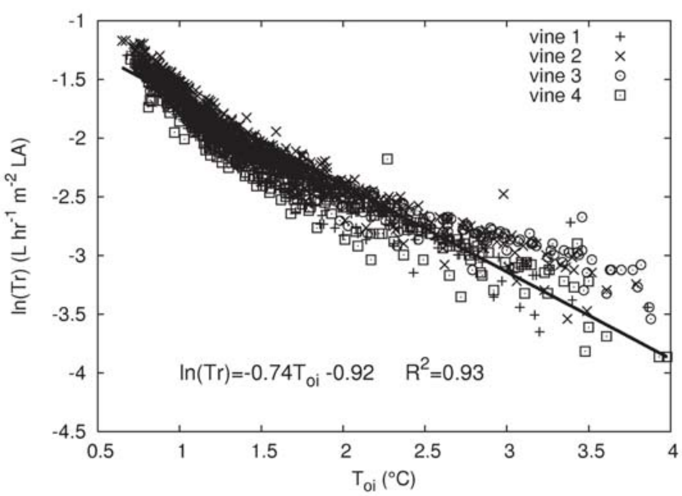

Figure 2 Log-transform of the calibrated transpiration rates per unit LA of four SC vines used in conjunction with canopy chambers versus the difference in stem temperature between upstream and downstream thermocouples of heat-balance sap-flow gauges (T_{oi}). The combined linear relationship (solid line) was used to estimate the transpiration of the other six experimental vines.

length category estimated visually from the dimensions of the remaining shoot.

Reference evapotranspiration and canopy conductance. Grass reference evapotranspiration (ET_0) was estimated using the modified Penman-Monteith equation (Allen et al. 1998). Wind speed, total solar radiation, air temperature, and vapor pressure deficit were acquired by the following sensors, positioned 5 m aboveground over an adjacent orchard: (1) cup anemometer (03001, Campbell Scientific); (2) pyranometer (LI-200SZ, LI-COR, Lincoln, NE); and (3) humidity/temperature probe (HMP35C, Campbell Scientific). A short-term comparison between values obtained at 5 m above the orchard and at 2 m above a nearby grass field showed that on an hourly basis, there were no differences in relative humidity and temperature measurements between heights. For practical purposes, we used the measurements from the above-orchard system and applied a height correction on wind speed (Allen et al. 1998). Net radiation was estimated from total solar radiation, while soil heat flux was assumed to be 10% of net radiation during the day and 50% at night (Allen et al. 1998).

Crop coefficients (k_c; dimensionless) were calculated as

$$k_c = \frac{T}{ET_o}$$

where T is measured transpiration. These coefficients must be considered *basal crop coefficients* (Allen et al. 1998), which includes only vine transpiration and no water loss from the soil or other plants. This measurement can be useful for drip-irrigated vines where water is applied under the vines so soil evaporation is minimal. It is appropriate for transpiration estimates of the vines rather than the entire vineyard.

Hourly values of canopy conductance (g_c, m s^{-1}) were estimated according to Lu et al. (2003)

$$g_c = \frac{\gamma \lambda E_c g_a}{\Delta R_n + 3600 \rho c_p VPD g_a - \lambda(\Delta + \gamma)T}$$

where γ is the psychrometric constant (kPa K^{-1}), λ is the latent heat of vaporization of water (MJ kg^{-1}), Δ is the slope of the relationship between saturation vapor pressure and temperature (kPa K^{-1}), T is measured transpiration (kg hr^{-1} m^{-2}), g_a is the aerodynamic conductance (m s^{-1}), ρ is the density of dry air (kg m^{-3}), c_p is the specific heat capacity of air (MJ kg^{-1} K^{-1}), VPD is measured vapor pressure deficit (kPa), and R_n is the net radiation absorbed by the canopy (MJ m^{-2} hr^{-1}), estimated by assuming a spherical leaf distribution and 80% of the canopy was always sunlit. The aerodynamic conductance (g_a, m s^{-1}) was estimated according to Yunusa et al. (2000) as

$$g_a = \frac{62.87}{(1 + 0.54u)}$$

where u is measured wind speed (m s^{-1}).

Results

The experimental season was characterized by two periods: cool and humid in June and July and hot and dry during August. Daily maximum VPD averaged 2.4 kPa during the first days of August, compared with an average daily maximum VPD of 1.8 kPa during June and July. Precipitation was distributed over the season, but with two periods of relative drought during the beginning of July and the beginning of August. The dry period in August was also characterized by the onset of high temperatures, resulting in unusually high evaporative demands. Total LA for each of the 10 half-vines at the end of the season was 9.23 ± 0.95 m^2 for GDC and 7.75 ± 0.96 m^2 for SC. Air temperatures inside the gas exchange chambers were somewhat higher than ambient, particularly early in the afternoon, with maximum differences ~6°C. This increase in temperature probably did not appear to cause significant stress in the vines, given the short period in which the canopies were enclosed by the chambers.

No evidence of time lag was observed between heat-balance and canopy-chamber systems (Figure 3). Correlation and regression analyses were separately performed on each half vine. There was a high degree of correlation between measurements from canopy chambers and gauges (correlation coefficients ranging from 0.94 to 0.96); however, the slopes of the linear relationships varied markedly among vines (0.84 to 1.51) with three gauges overestimating transpiration (Figure 4).

Daily maximum transpiration rates per whole vine ranged from 2 to 5 L hr^{-1} for GDC vines and from 2 to 4 L hr^{-1} for SC vines, as seen in an example of daily patterns for three consecutive days (Figure 5). Total daily transpiration per unit LA ranged between 1.0 and 2.3 L day^{-1} m^{-2} LA^{-1}. Daily cumulative transpiration per whole vine for the entire experimental period peaked ~40 L day^{-1} during early July, gradually declining after the end of July (Figure 6).

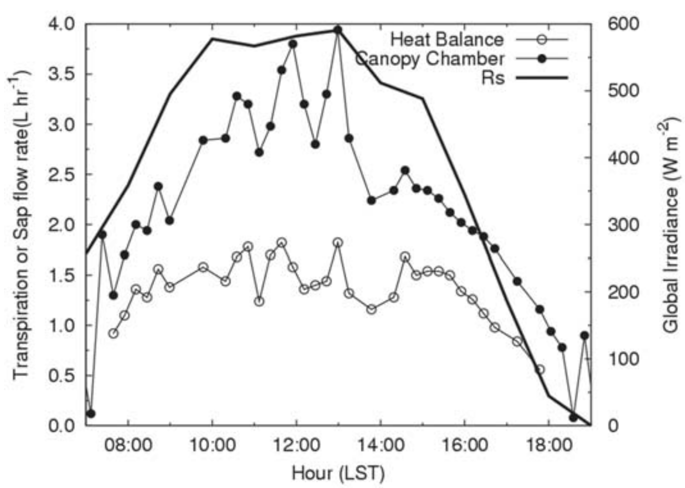

Figure 3 Instantaneous transpiration and sap-flow rates on 25 Aug as estimated using a whole-canopy gas exchange chamber and heat-balance sap-flow gauge on vine 1 (values are for one-half vine, the canopy supported by a single trunk). Solid line describes global irradiance (**Rs: global irradiance**).

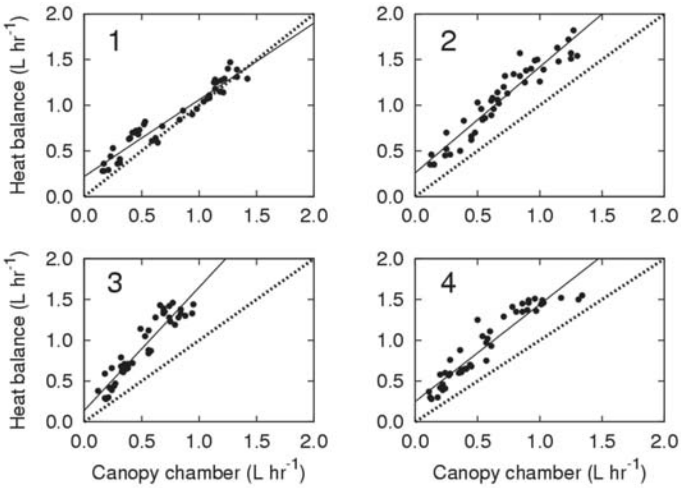

Figure 4 Regression analyses between sap-flow and canopy-chamber transpiration rates (hourly averages) for each of four SC vines. Dotted lines represent 1:1 relationship; results from the linear regression analysis were for vines 1, 2, 3, and 4 (solid lines): $y_1 = 0.84\ x_1 + 0.22$, $R^2 = 0.93$; $y_2 = 1.16\ x_2 + 0.26$, $R^2 = 0.91$; $y_3 = 1.51\ x_3 + 0.15$, $R^2 = 0.88$; $y_4 = 1.19\ x_4 + 0.15$, $R^2 = 0.89$.

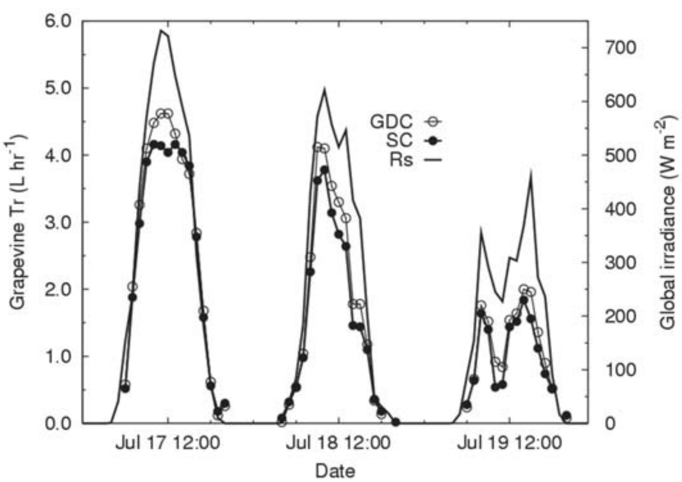

Figure 5 Hourly whole-vine-transpiration rates (average for each training system) during three consecutive days (**Rs: solar irradiance**).

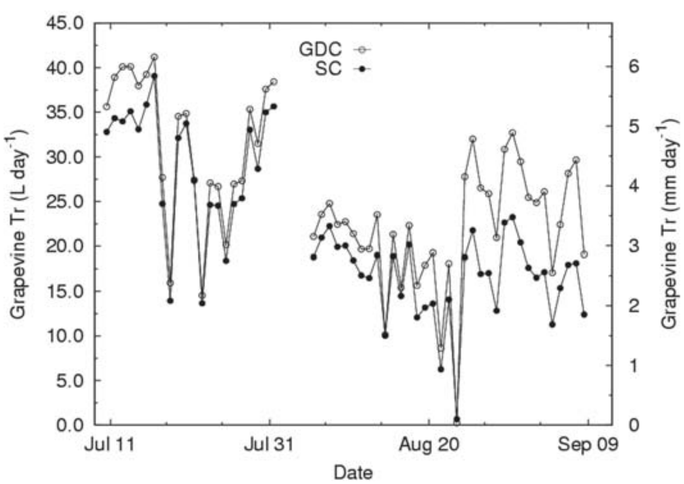

Figure 6 Daily water use per vine (average of all vines in the same training system; n = 4 GDC, n = 6 SC) and grass reference ET_0 during the experimental season.

On average, GDC vines transpired 12% more than SC (SC = 0.88×GDC, $R^2 = 0.98$) during July, although transpiration per unit LA was similar (SC = 1.04×GDC, R^2=0.98). During August, vines in both training systems showed a substantial reduction (≈33%) in transpiration, with maximum values approaching 25 L day^{-1}. While GDC partially recovered during September, SC maintained lower transpiration rates per vine (SC = 0.75×GDC, $R^2 = 0.97$) and per unit LA (SC = 0.87×GDC, $R^2 = 0.97$).

Estimated daily maximum canopy conductance g_c averaged 4.4 m s^{-1} (≈160 mmol m^{-2} s^{-1}) for GDC and 5.1 m s^{-1} for SC (≈200 mmol m^{-2} s^{-1}), during July (Figure 7). A decrease was observed during August, with GDC averaging 3.0 m s^{-1} and SC 2.9 m s^{-1}. Average maximum daily g_c in GDC vines was higher during September, equaling the July value of 4.4 m s^{-1}; SC vines showed also higher g_c, with a daily maximum average of 3.5 m s^{-1}, 30% less, however, than what was observed in July.

Calculation of k_c included only those measurements collected before the dry period in August. Estimated daily basal crop coefficients were highly variable (Figure 8): average k_c was 1.16 ± 0.10 for GDC and 1.06 ± 0.09 for SC. Estimated total transpiration for July by using the reference grass-based crop coefficient model was 99 mm for GDC and 90 mm for SC, very close to the sap-gauge estimated water use of 98 mm for GDC and 90 mm for SC. A significant degree of correlation was observed between daily crop coefficients and daily average VPD, ($R^2 = 0.39$ for GDC; $R^2 = 0.57$ for SC; $p < 0.01$ in both cases).

Discussion

Seasonal patterns of transpiration were similar for all 10 vines, indicating that physiologically the plants responded similarly to the local environment. Slightly larger leaf areas (15%) and higher light interception by the canopy probably caused the 10% greater daily transpiration in GDC vines than in SC vines. Expressed per unit

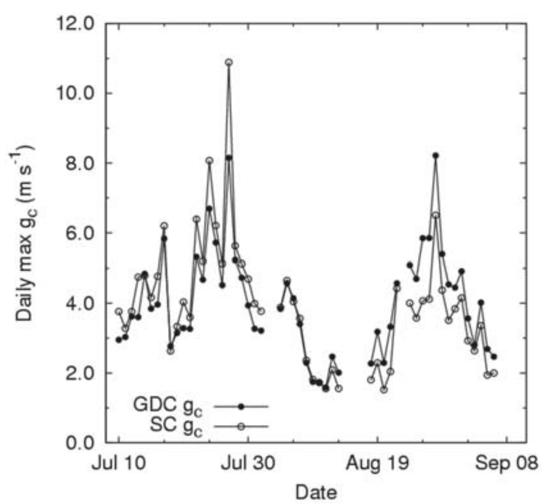

Figure 7 Estimates of daily maximum canopy conductance for GDC and SC vines during the experimental period.

LA, daily transpiration was similar between training systems, especially during July before the onset of the hot, dry period in August. With canopy division (i.e., GDC), higher average exposure to solar radiation per unit LA would be expected and, consequently, higher rates of transpiration per unit LA, assuming transpiration to be driven predominantly by net radiation. Concurrently, higher rates of photosynthesis would be expected to accompany the higher rates of transpiration. However, because the sap-flow gauges on the GDC vines were calibrated indirectly from the chamber-gauge relationship (Figure 2) derived from SC vines, there may have been an error introduced into the gauge-based transpiration estimates computed for the GDC vines.

Given the realistic but simplified model used to estimate net radiation, it is likely that absolute values of canopy conductance may include a systematic error. However, the relative magnitude and the temporal pattern of canopy conductance provide a reliable indicator of vine response to the environment. In this respect, the reduced rates of transpiration in both GDC and SC vines during August coincided with a roughly proportional decrease in canopy conductance (≈30 to 40%, Figure 7), indicating that the dry and hot weather decreased transpiration by inducing partial stomatal closure. The wide (15 to 22 cm), broad shape of mature Concord leaves with few indentations increases leaf boundary layer resistance, in turn limiting sensible heat transfer. Thus, a substantial and rapid increase in leaf temperature among exposed leaves may occur even during conditions of partial stomatal closure. In this case, the hot and dry conditions of August may have induced heat stress, and thus lower transpiration rates later in September, especially in SC vines, where transpiration per unit of LA was lower than GDC, and stomatal conductance was about 70% of what observed in July.

To the best of our knowledge, there are no reports in the literature of water-use rates for mature *V. labruscana* grapes in a humid and cool climate. Tarara and colleagues

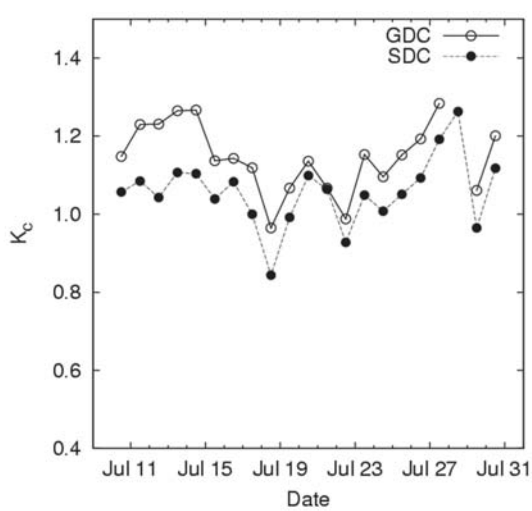

Figure 8 Daily basal k_c for GDC and SDC vines during July, a period with no apparent water stress.

(2002, unpublished data) estimated the rates of Concord vines in the arid, warm climate of eastern Washington state and found that vines with a spacing similar to those reported here but with larger leaf area (~22 to 28 m^2 versus 16 to 18 m^2) were transpiring up to 30 L day^{-1}, or ~1.0 to 1.4 L day^{-1} m^{-2} LA. Transpiration in the vineyard reported here was significantly higher, especially during July; however, transpiration rates per unit LA in Washington were similar to those measured in New York grapevines during the warmer month of August. Concord grapevines are native to the humid northeastern United States, so it is possible that in both cases (i.e., under arid, warm weather) water stress induced partial stomatal closure, reduced transpiration, and raised leaf temperature.

In the cool, humid climate of Germany there have been field studies of water use in Riesling and other *Vitis vinifera* L. cultivars with Granier-type sap-flow gauges (Braun and Schmid 1999) that gave peak values of about 1 L day^{-1} m^{-2} LA (2.0 to 2.5 mm day^{-1}). These rates are ~40 to 50% of the maximum rates found here (Figure 5). Water use in *V. vinifera* was measured with a lysimeter in the hot and dry climate of California (Williams et al. 2003b): daily transpiration rates were comparable to or slightly higher than the rates we measured in New York in *V. labruscana* in July. However, in California, seasonal ET_0 was almost twice that measured during our experiment.

Reported rates of midsummer transpiration in *V. vinifera* using both heat-pulse and heat-dissipation sap-flow gauges in the hot, dry climate of Australia were 4 to 5 times less than those measured in the present study (Yunusa et al. 1997, 2000, Lu et al. 2003). In these reports canopy conductance seemed to be strongly limited by evaporative demand (VPD up to 8 kPa), with conductance values comparable to our observations only during the early morning (≈400 mmol s^{-1} m^{-2} LA; D. Dragoni 2002, unpublished data). Given published values, the rates of transpiration measured here are striking because of generally low evaporative demand in our climate. However, direct comparison among studies can be difficult because of the differences in varieties, training systems, agricultural practice, level of plant stress, and environmental conditions (Williams et al. 2003b). Variation among measurement techniques can also affect results, as can differences in leaf area and light interception; leaf size, as large leaves warm well over air temperature, giving high leaf to air vapor pressure gradients at moderate air temperatures; and high transpiration rates of Concord leaves under optimal conditions. We have measured in other cases Concord leaf conductances of 700 mmol m^{-2} s^{-1}, giving over 10 mmol m^{-2} s^{-1} transpiration rates (A. Lakso and D. Dragoni 2002, unpublished data). A lack of direct calibration in the field for other sap-flow studies may also contribute to apparent differences among reports.

The reference grass-based crop coefficient model assumes that k_c adjusts exclusively for structural and physiological differences between grass and vines (Allen et al. 1998), so it is not expected to show high fluctuations on a short timescale. However, calculated daily basal crop coefficients were highly variable over time, indicating that the reference grass-based crop coefficient model could not predict short timescale changes in vine transpiration, likely because of the high degree of coupling between stomatal regulation and the bulk air, compared to reference grass, where transpiration is driven primarily by net radiation (McNaughton and Jarvis 1991, Lu et al. 2003). The reference grass-based crop coefficient model lacks sensitivity because it assumes that grass and vine responses to changes in weather are proportional in direction and intensity, and thus k_c varies predominantly with the specific crop characteristics (Allen et al. 1998). Observations here, however, showed a positive correlation of k_c with VPD ($p < 0.01$ for both GDC and SC), indicating that vines are more sensitive than reference grass to changes in bulk air VPD. Nevertheless, when the average k_c for July was applied to daily ET_0, the reference grass-based crop coefficient model estimated total GDC and SC water use for that period with a difference less than 1% from the values estimated by the sap-flow gauges. That is because VPD fluctuations were mainly random during July, and the use of the monthly average k_c caused the errors on transpiration estimates obtained using the crop coefficient model to compensate each other.

Conclusion

Estimated rates of transpiration were higher than those reported elsewhere because the cooler and more humid climate in the present study induced less water stress than presumably occurred in other regions (such as Australia and California). Direct comparison with other geographical areas is difficult because of differences in varieties, training systems, and measurement techniques. However, in concurrence with other reports, the Concord vines in this study showed high susceptibility to erratic periods of dry and hot weather (e.g., early August), probably because of species adaptation to lower overall evaporative demand during the growing season. This issue is important to consider in that climate-change predictions for the northeastern United States generally suggest a higher frequency and severity of erratic droughts. For this reason, water-use models based on reference grass may be insufficient for irrigation management, as they underestimate the degree of coupling between stomatal regulation and bulk air conditions. Furthermore, they lack sensitivity to frequent changes in weather. Ultimately, as irrigation becomes important in growing grapevines even in the humid climate of the northeast, research should focus on quantifying transpiration and its environmental driving forces and on developing species-specific physiological models to predict water use at local and regional scale.

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