Two Algorithms for Variable Power Control of Heat-Balance Sap Flow Gauges under High Flow Rates

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ABSTRACT

The advantages of variable power control for heat-balance sap flow gauges are evident under high flow rates (e.g., >600 g h^{-1}) where high rates of power must be applied. Under the very high flow rates (e.g., 1500–4000 g h^{-1}) of mature grapevines (*Vitis* spp.), we evaluated two algorithms to control the power applied to heat-balance sap flow gauges, and thus the temperature difference (ΔT) above and below gauge heaters: (i) a proportional-derivative (PD) algorithm and (ii) an open-loop controller following the theoretical diurnal course of irradiance. The PD algorithm was tuned for expected maximum flow rates and could keep ΔT within 0.1°C of its daytime (0800–1800 h) target value. Over 21 d, mean daytime ΔT was 1.32 ± 0.001°C (s.e.m.) for an 18-gauge system. The algorithm was unstable early in the morning and in the evening as rates of sap flow were below those for which the algorithm had been tuned. In the open-loop algorithm, power output was programmed to change according to a sine curve tied to daylength. In well-watered vines, the power curve mimicked actual sap flow patterns. As flow rates varied it accommodated the changing dead time of the system, which is the delay or time required before any change in ΔT occurs. Daytime ΔT varied sinusoidally with a typical amplitude of 0.5 to 1.0°C. The coefficient of variation in daytime ΔT appeared to be higher (16–26%) under the open-loop algorithm than under the PD algorithm (5–13%). Under weekly cycles of deficit irrigation, the variance in daytime ΔT increased with the number of days after irrigation, suggesting that the open-loop algorithm might best be applied when the stem energy balance includes an estimate of heat storage.

THE heat balance method of measuring sap flow in plants is well documented (e.g., Dugas, 1990; Grime and Sinclair, 1999; Smith and Allen, 1996). Briefly, one uses a heat balance equation to determine convective energy transport in the transpiration stream. This is accomplished by applying a known amount of energy to a flexible heater encircling the stem, measuring radial and vertical temperature gradients, and determining heat dissipation from the stem segment:

$$Q = Q_r + Q_v + Q_f + Q_s \qquad [1]$$

where Q is heat input to the sap flow gauge, Q_r is heat conducted radially from the gauge, Q_v is heat conducted axially up and down the stem tissue, Q_f is heat convected in the transpiration stream, and Q_s is heat stored by the stem, all in watts. Detailed derivations of individual terms in Eq. [1] can be found elsewhere (Baker and van Bavel, 1987; Sakuratani, 1981). Under steady state, Q_s

can be ignored. Equation [1] is solved for Q_f, from which one calculates the mass flow (F) of xylem sap:

$$F = Q_f/(c_p \Delta T) \qquad [2]$$

where c_p is the heat capacity (J g^{-1}°C^{-1}) of xylem sap, usually taken as the heat capacity of water, and ΔT is the difference in stem temperature (°C) above and below the heater. Most often F is expressed in g h^{-1}.

The sap flow gauge heater may be controlled in either constant or variable power modes. Constant power necessitates a compromise between a sufficiently low Q so as to not damage the stem by overheating during periods of low flow, and a sufficiently high Q for high flow rates so as to maintain a reasonable ΔT with an adequate signal/noise ratio, often about 2°C for thermocouple measurements. However, as flow rates rise ΔT decreases, causing significant errors in estimates of F if ΔT becomes too small (Ham and Heilman, 1990).

The variable power approach to heat-balance sap flow gauges was devised partly to address violations of the steady state assumption. As the name implies, this approach varies Q via a control circuit and an algorithm that accounts for change in ΔT with the objective of maintaining a nearly constant ΔT. Advantages of the variable power method are that there is less likelihood of overheating the stem; there is a stable signal/noise ratio for ΔT; and perhaps most importantly, Q_s is minimized (Grime et al., 1995b), which also may appear to improve response time. One variable power algorithm (Ishida et al., 1991) used an empirically derived proportional gain factor (G) based on the difference between ΔT and its target value to vary the on-time of a heater control circuit. The controller performed well on small herbaceous stems with flow rates up to 80 g h^{-1}. Other researchers have modified and applied the "Ishida" technique on small trees (Grime et al., 1995b [flows up to 200 g h^{-1}]; Weibel and de Vos, 1994 [flows up to 120 g h^{-1}]) but reported difficulty with larger plant stems, higher flow rates, and under conditions of rapidly changing rates of sap flow.

For plants with high flow rates, one limitation of proportional-gain algorithms is that G alone may be insufficient: one assumes a single time constant when the system actually contains multiple time constants and variable dead time over the course of a day. Dead time refers to the delay in the loop due to the time required for xylem sap to flow from the upstream to the downstream thermocouple, or the time required before any change in ΔT occurs. One solution to the challenges of variable-power control is to write more sophisticated feedback-

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Abbreviations: *D*, damping factor; DOY, day of year; *G*, empirically derived proportional gain factor; K_g, zero-flow gauge conductance; PD, proportional-derivative algorithm.

loop algorithms, including those that are self-tuning (Gawthrop, 1996; Sebakhy, 1996), although the variable power method already is computationally intensive. A simpler approach to variable power control algorithms could be useful to biological and agricultural researchers who apply the heat-balance technique in the field to plants with high rates of sap flow (e.g., >600 g h^{-1}) like trees, vines, or other large perennial crops.

Our objective was to evaluate two algorithms to control the power applied to heat-balance sap flow gauges and thus ΔT under high rates of sap flow ($\approx$1000–4000 g h^{-1}) in the field: (i) a proportional-derivative (PD) algorithm and (ii) an open-loop controller. The PD or feedback-loop algorithm (Campbell et al., 1995) varies Q proportionally with G and a damping factor (D) for the time-derivative of ΔT. The open-loop algorithm that we developed is based on daylength and the theoretical diurnal course of irradiance. Its purpose is easy application by any scientist with working knowledge of the heat-balance sap flow technique and dataloggers. We chose to work with grapevines as our test crop because vines in general have a high ratio of leaf area per unit stem cross-sectional area, suggesting efficient transport of water and the potential for high flow rates (Carlquist, 1985; Ewers et al., 1991). On established vines, relatively small diameter stems make them amenable to the heat-balance technique.

MATERIALS AND METHODS
Proportional Derivative Algorithm

We modified for analog control a PD algorithm (Campbell et al., 1995) originally designed to apply up to 1-s long heat pulses via digital control

$$Q_{t+1} = Q_t + G\left[(\Delta T_{target} - \Delta T) - D\frac{dT}{dt}\right] \quad [3]$$

where Q_t is the power currently output to the gauges, Q_{t+1} is the power to be output during the next program execution (5 s), and ΔT_{target} is the desired value of ΔT. The dT/dt was calculated for the previous 1 min, then multiplied by D to determine a projected ΔT. From this, Q_{t+1} was set for the next execution interval. Values of G and D were determined empirically by iterative tuning for the expected mid-day flow rates of mature grapevines (Tarara and Ferguson, 2001). A maximum allowable value of Q (Q_{max}) was input and was adjusted periodically to accommodate the substantial increases and decreases in transpiration (i.e., sap flow) as canopies grew and senesced. At night, the program defaulted to a predetermined minimum value (Q_{min}) so that low flows could be measured while minimizing the risk of overheating the stem.

Solar Algorithm

Under clear skies, the diurnal course of irradiance is a function of one's latitude and day of year (DOY), and is approximately sinusoidal (Monteith and Unsworth, 1990, Eq. [4.8]):

$$S_t = S_{tm} \sin(\pi h/n) \quad [4]$$

where S_t is total irradiance on a horizontal surface, S_{tm} is the maximum irradiance at solar noon, h is time (h) after sunrise, and n is daylength in hours. Sap flow has been shown to follow

the diurnal curve of irradiance in many woody plants (e.g., Gutiérrez et al., 1994; Weibel and Boersma, 1995) including vines (Braun and Schmid, 1999; Fichtner and Schulze, 1990; Green and Clothier, 1988). Should Q change proportionately with irradiance, ΔT should remain nearly constant and Q_s negligible (Eq. [1], [2]) as sap flow rises and falls over the course of the day.

The time of sunrise, sunset, and daylength can be calculated from one's latitude, DOY, and the time of solar noon through a series of equations available in physical climatology or environmental physics texts (e.g., Campbell and Norman, 1998; Monteith and Unsworth, 1990). However, to simplify the calculations by the datalogger we accessed astronomical tables (U.S. Naval Observatory) listing daily times of sunrise and sunset for our location (near Prosser, WA; 46.2° N, 119.8° W). Using stepwise linear regression, fourth-order polynomials were fit between DOY and time of sunrise [$y = 12.6 - 0.1051x + (3.027 \times 10^{-4})x^2 + (4.143 \times 10^{-6})x^3 - (1.051 \times 10^{-9})x^4$], and DOY and time of sunset [$y = 21.3 - 0.1229x + (1.536 \times 10^{-3})x^2 - (6.573 \times 10^{-6})x^3 + (8.852 \times 10^{-9})x^4$] from April through October (DOY 91–304), the period of our field measurements. The datalogger software (PC208W, Campbell Scientific, Logan, UT) included commands for determining DOY and for inputting polynomial equations, thus minimizing the number of instructions required in an already large sap flow program. Details of the datalogger program can be obtained directly from the authors.

To accommodate an extended dawn and dusk during which stomates may be open, the datalogger calculated a start time (t_{start}) for the power controller of 60 min before sunrise and a stop time (t_{stop}) of 60 min after sunset. At each execution (15 s), the program computed the current time's (t) position on the daily curve (P_{time}), defined as the fraction of the current sap flow day that began at t_{start} and ended at t_{stop}. The P_{time} was modeled as a sine wave, shifted in phase, inverted, and scaled:

$$P_{time} = \left(\sin\left\{\left[\left(\frac{t - t_{start}}{t_{stop} - t_{start}}\right)360\right] + 90\right\}\right)(-0.5) + 0.5 \quad [5]$$

where all times are in hours into the current day. Power output to the gauge was then calculated as

$$Q = (Q_{max} - Q_{min})\,P_{time} + Q_{min} \quad [6]$$

where Q_{max} is the maximum and Q_{min} the minimum amount of power allowed. Values for Q_{min} and Q_{max} were selected from evaluation of previous years' flow rates (data not shown) and daily trends in ΔT. As with the PD algorithm, Q_{max} was adjusted periodically as canopies grew or senesced, which increased or decreased transpiration. At night, power defaulted to Q_{min}. To prevent stem overheating during rainy days or extended periods of cloud, a high temperature limit was set for ΔT, at which point the datalogger output $0.25Q$ to the power controller for the remainder of the day.

Field Experiment

Heat balance sap flow gauges were scaled-up from the design of Senock and Ham (1993) for the larger stems and high flow rates of mature grapevines. Multiple sizes of gauge were constructed to cover the range of trunk diameters in two vineyards. Heater widths (Heater Designs, Bloomington, CA) were approximately twice the diameter of the vine trunks. To sample adequately the temperatures around the stem, gauges included eight thermopile junctions. Up- and downstream temperatures were measured at the trunk surface but at relatively long distances from the heater (35 mm for deficit-irrigated vines and 100 mm for well-watered vines), where thermal homogeneity

across the trunk was expected at high flow rates (Tarara and Ferguson, 2001). The inherent compromise in this arrangement is an increase in dead time. Initial values for the zero-flow gauge conductance (K_g) were estimated in the laboratory on severed vine trunks; in the field K_g was reset daily to its lowest predawn value. Following the method of Steinberg et al. (1989) we computed the thermal conductivity of the trunk (0.42 W m^{-1}°C^{-1}) from relative volumes occupied by wood, water, and air, and the thermal conductivity of dry grapevine trunk tissue that had been analyzed for us (Thermophysical Properties Laboratory, Purdue University, W. Lafayette, IN).

The analog power control circuit of Weibel and Boersma (1995) was modified only by substituting locally available components. In the laboratory, the performance of the gauges was compared with gravimetric measurements for flow rates up to 3000 g h^{-1} (Tarara and Ferguson, 2001). The gauges consistently underestimated sap flow, with the largest relative errors occurring at low flow rates. Between ≈250 and ≈3000 g h^{-1}, instantaneous estimates (i.e., 5 or 12-min signal averaging depending on the specific test run) from the gauges were on average 7% less than gravimetric measurements. For cumulative flows of 4.4 to 14.4 kg over several hours, the range of underestimation by the gauges during various tests was 1.5 to 15%.

In two commercial vineyards, up to 45 gauges were operated simultaneously from May to October during 2000 to 2003. In 2000 and 2001, 18 gauges were deployed on 'Concord' grapevines (Vitis labruscana Bailey) planted in 1990 and grown for juice concentrate. Trunk diameters ranged from 32 to 42 mm. Mid-season leaf area varied from 21 to 28 m^2 per vine. Vines were well-watered by furrow (2000) and overhead sprinkler (2001) irrigation. Twenty-seven (2001, 2003) and 36 (2002) gauges were installed on 'Cabernet Sauvignon' grapevines (Vitis vinifera L.) planted in 1992, from which two trunks had been trained above a single crown and root system. Trunk diameters varied between 29 and 37 mm. A gauge was installed on only one of the two trunks per vine. Mid-season leaf area was between 3 and 5 m^2 per trunk. Vines were deficit-irrigated by drip, the standard practice for wine grape vineyards in Washington State.

Before gauge installation on both species, all loose bark was removed down to a smooth periderm surface to ensure good stem-to-thermocouple contact. Gauges were positioned so that the heater and the above- and below-heater thermopiles were between nodes. All gauges were insulated with closed-cell polyethylene foam (3.8 cm thick; thermal conductivity = 0.042 W m^{-1} K^{-1}) and wrapped with aluminum foil, both extending to the soil surface to minimize environmentally induced temperature gradients along the stem (Gutiérrez et al., 1994). Every 3 wk, gauges were removed from Cabernet Sauvignon vines for 3 to 5 d then reinstalled. On Concord vines, which had taller trunks, the same schedule was followed except that gauges could be moved up or down the stem and reinstalled within 24 h. No damage was observed on any trunk due to uninterrupted sap gauge operation as long as its duration did not exceed 1 mo, beyond which we observed adventitious roots emerging under some gauge heaters.

For each set of nine gauges, the data acquisition and control system consisted of one datalogger (CR10X, Campbell Scientific, Logan, UT) and two relay multiplexers (AM-416, Campbell Scientific, Logan, UT). Signals were recorded every 5 s (PD algorithm) or 15 s (solar algorithm) and averaged every 12 min. All systems were powered by arrays of solar panels (up to 360 W total). For deficit-irrigated Cabernet Sauvignon vines midseason Q_{max} was around 3.0 W, whereas for well-watered Concord vines midseason Q_{max} approached 6.5 W. For both species, Q_{min} was 0.2 W.

Both control algorithms were analyzed for their ability to maintain a nearly constant daytime ΔT (0800–1800 h). Two nine-gauge systems running in Concord grapevines were included in the analysis. Only one nine-gauge system from the Cabernet Sauvignon grapevines study was included in the analysis because this system was within the field treatment that represented the standard industry irrigation practice. Removed from the data set were rainy days in which the power "fail safe" was invoked. Data also were excluded if ΔT was <0.5°C, a lower boundary set to eliminate the known overestimation of F that occurs when ΔT is too low (Ham and Heilman, 1990). Gross violations of steady state before 09.00 h that resulted in computed flow rates >1000 g h^{-1} (Cabernet Sauvignon vines) or >2000 g h^{-1} (Concord vines) were eliminated, as these were caused by phenomena outside the control of Q by the algorithm. Descriptive statistics were calculated for both algorithms using SAS (v. 9.1.3, SAS Inst., Cary, NC).

RESULTS AND DISCUSSION
Proportional Derivative Algorithm

The grapevines in these experiments transpired at rates up to one order of magnitude greater than those encountered by other researchers using the heat-balance sap flow method on grapevines (Braun and Schmid, 1999) or on other woody plants with stems of similar diameters as those in our study (e.g., Grime et al., 1995b; Gutiérrez et al., 1994; Weibel and de Vos, 1994). The sap flow rates that we recorded were lower than those observed via stem heat balance in some tropical vines (Entadopsis polystachya A. Chev.; Fichtner and Schulze, 1990) and via heat-pulse sensors in cultivated kiwifruit vines (Actinidia deliciosa L.; Green and Clothier, 1988). With gauges installed on large Concord vines, the PD algorithm, tuned (i.e., G and D selected) for high flow rates (>1500 g h^{-1}) generally maintained ΔT near its target value of 1.3°C (Fig. 1). Higher values of ΔT (2 to 3°C) consistently were maintained during subsequent seasons, but power constraints at the field site during 2000 limited the maximum obtainable Q to around 4.5 W and thus restricted our selection of ΔT_{target}. For the gauge in Fig. 1, daytime ΔT averaged 1.31 ± 0.06°C. In the 18-gauge system over 21 d, the mean daytime ΔT was 1.32 ± 0.001°C (s.e.m.) ranging between 1.26 ± 0.005°C (s.e.m.) and 1.36 ± 0.01°C (s.e.m.) for any single gauge. Given the accuracy of a thermocouple-based temperature measurement (± 0.2°C), such small variances around these means suggest excellent control of Q for constant ΔT. The diurnal pattern of sap flow in these well-watered vines followed that of irradiance with the exception of an apparent anomaly (ca. 0700–0900 h) due to a violation of the steady state assumption.

Transpiration varies along two temporal scales: one diurnal and one in response to transient disturbances like passing cloud. Typically, one tunes a proportional-gain or PD power control algorithm empirically for expected maximum rates of sap flow. We expected more stability from a PD algorithm than from a simpler proportional-gain type of algorithm because the PD algorithm includes a time-derivative term. Despite iterative tuning throughout the growing season, power control by the PD algorithm in this experiment often became unstable during morning and evening primarily because D had been set for the high flow rates of midday
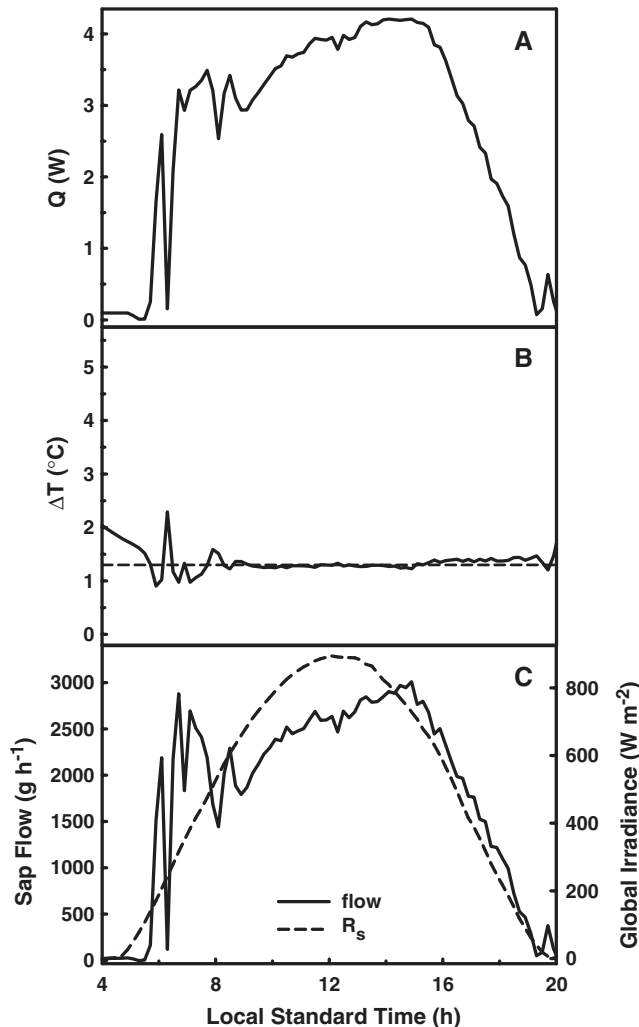
Fig. 1. Typical daytime course of (A) power (Q); (B) temperature difference between upstream and downstream thermopiles (ΔT), with dashed line representing ΔT_{target} of 1.3°C.; and (C) sap flow and global irradiance (R_s) under clear skies for a representative heat-balance sap flow gauge on a 10-yr-old well-watered Concord vine in a semiarid environment. The gauge was operated under variable power control using a PD algorithm. Data were collected DOY 202, 2000. Overnight, Q was held at 0.2 W to avoid overheating the stem.
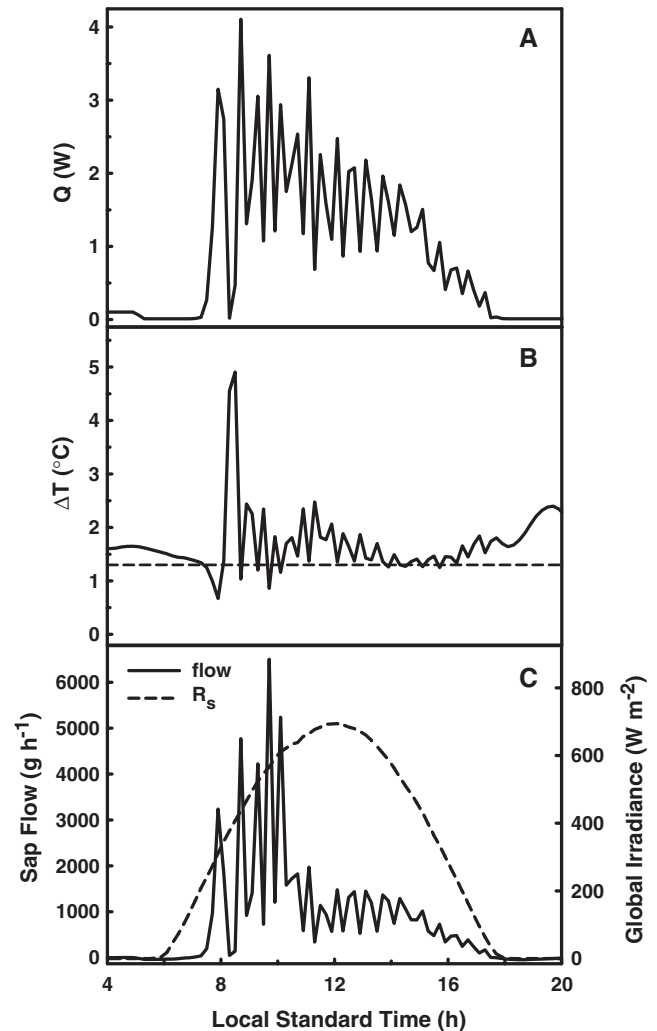
Fig. 2. Example of protracted oscillation in power control by the PD algorithm for a representative heat-balance sap flow gauge on a 10-yr-old well-watered Concord vine in a semiarid environment, when flow rates were below those for which the algorithm had been tuned. (A) Power to the gauge heater (Q); (B) temperature difference between upstream and downstream thermopiles (ΔT), with dashed line representing ΔT_{target} of 1.3°C.; (C) sap flow and global irradiance (R_s). Data were collected DOY 269, 2000.

hours. Thus, D was too small for the dead time of the system at times of day dominated by low but rapidly changing flow rates. At times, excessive response to the deviation between ΔT and ΔT_{target} led to oscillation in Q so that sap flow rates appeared to oscillate for periods of several hours to the entire day (Fig. 2), an artifact not uncommon among proportional controllers (Shaw, 2001). Overall, power control under the PD algorithm appeared unstable during times in which sap flow rates were much lower than those for which the algorithm had been tuned and during times of large rate changes in flow, but during midday the control of ΔT was excellent.

Maximum rates of sap flow in the deficit-irrigated Cabernet Sauvignon vines ($\approx$1200–1700 g h^{-1}) were much lower than those in the well-watered Concord vines ($\approx$3000–3800 g h^{-1}), but exhaustive tuning of the PD algorithm at the Cabernet Sauvignon vineyard did

not resolve the frequent occurrence of protracted oscillation in Q, ΔT, and F (data not shown). While tuning an algorithm frequently may achieve good power control on some gauges, power control may be unstable on other gauges connected to the same data acquisition and control system (Campbell et al., 1995) because of considerable plant-to-plant variability. This is a legitimate concern in large field experiments that deploy many sap flow gauges. Operationally, one might consider dedicating a multi-gauge controller to a particular species or plant type in ecological studies. In an agricultural setting, a multi-gauge controller might be assigned to a set of sample plants with similar leaf areas to minimize between-plant variation in sap flow and allow the single output voltage from the controller to result in more uniform ΔT across gauges. In our case, algorithm instability in Cabernet Sauvignon grapevines may have been

exacerbated less by vine-to-vine variability than by the large variation across all gauges in daily maximum rates of sap flow (e.g., 400–1400 g h^{-1}) over a short period because the vines were managed under regulated deficit irrigation with a 7-d dry-down and rewetting cycle.

In constant power mode, substantial violations of steady state were apparent during periods of low flow (Fig. 3; same gauge and vine as in Fig. 2) in Concord grapevines, demonstrating the limitations of setting a single Q for plants with high mid day rates of sap flow. In this instance, a relatively stable ΔT for about 5 h in the middle of the day suggests that Q had been set appropriately for capturing mid-day measurements, although because it was after harvest, maximum flow rates were somewhat low ($\approx$1000 g h^{-1}) for this vineyard. The anomalously high values of sap flow around 10.00 LST demonstrate the gross errors that can occur if ΔT is too small (0.3–0.4°C in this case).

Solar Control Algorithm

Fourth-order polynomials achieved their purpose of simplifying computation by accurately predicting the times of sunrise and sunset at our location between DOY 90 and DOY 305. The mean absolute value of the residuals was 2.1 min, ranging from 0.01 to 6.4 min. This open-loop algorithm should be manageable for most users of heat-balance sap flow gauges because location-specific astronomical data are readily available and the coding for Eq. [4] is straightforward. Without more complexity, its most useful application is in areas where clear skies dominate the measurement period. The sine function closely followed irradiance on cloudless days (Fig. 4), diverging only because of t_{start} at 1 h before astronomical sunrise and t_{stop} at 1 h after astronomical sunset.

Daytime ΔT varied more under the solar algorithm than it had under the PD algorithm during the previous season. For example, during 5 d when gauges were running in both species (DOY 206–210, 2001), the coefficient of variation in daytime ΔT under the solar algorithm was 16 to 26%, regardless of species or irrigation practice. By contrast, in the previous year under the PD algorithm (Concord grapevines), the daily coefficient of variation across gauges was between 4.6 and 13.3% (DOY 228–252, 2000). In both years, data were recorded under clear skies. For Concord vines, daily maximum flow rates per vine were similar between years. Under the solar algorithm, mid-day ΔT generally varied in a sinusoidal fashion with an amplitude of about 0.5 to 1.0°C (data not shown), fluctuating with the apparent water status of the vines. In the deficit-irrigated Cabernet Sauvignon vines, the smallest variance in daytime ΔT occurred 1 to 2 d after the weekly irrigation, whereas the largest variance occurred in the last 2 d (i.e., driest period) of the weekly cycle (Fig. 5). This trend held across gauges: mean daytime ΔT was 1.8 to 2.2°C in the 2 d following irrigation and 4.2°C at the end of the 7-d irrigation cycles (DOY 228–252, 2003). During
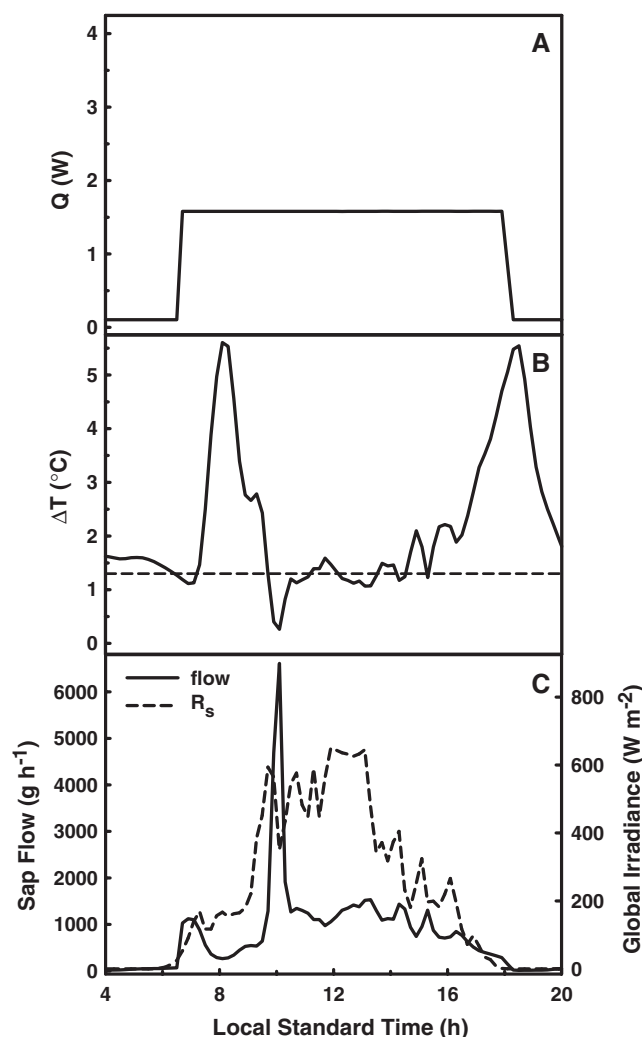

Fig. 3. Performance of a representative heat-balance sap flow gauge operated in constant power mode on a 10-yr-old well-watered Concord vine in a semiarid environment. (A) Power to the gauge heater (Q); (B) temperature difference between upstream and downstream thermopiles (ΔT), with dashed line representing ΔT of 1.3°C; (C) sap flow and global irradiance (R_s). The substantial error that can occur due to small ΔT is evident around 10.00 LST. Data were collected on DOY 272, 2000.
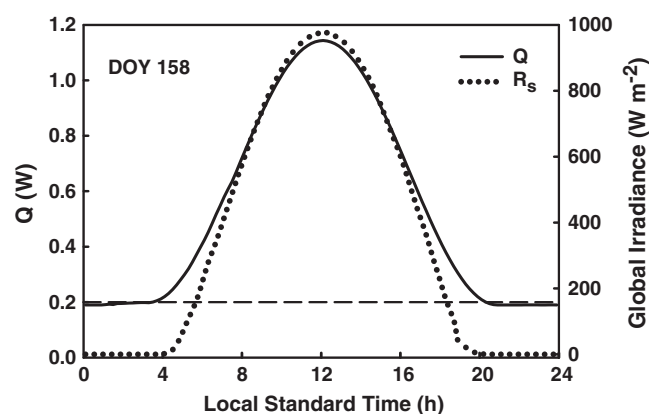

Fig. 4. Exemplary diurnal curve of power (Q) applied to the gauge heater by the open-loop algorithm on a day with clear skies. The divergence of Q from irradiance (R_s) at either end of daylight hours reflects the start time of the controller at 60 min before the computed value for sunrise and the stop time of the controller at 60 min after the computed value for sunset. Nighttime Q was held constant at 0.2 W (horizontal reference line).
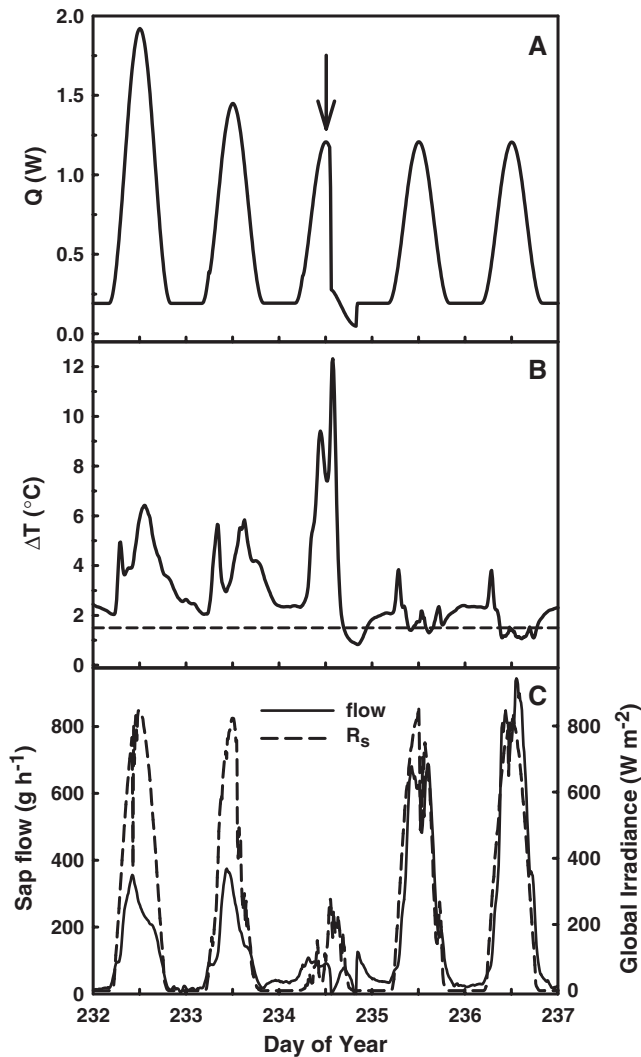
Fig. 5. Performance of an exemplary heat-balance sap flow gauge on deficit-irrigated Cabernet Sauvignon grapevines during 5 d encompassing the end of a weekly dry-down and rewatering. Irrigation was applied by drip (0.75 L h^{-1} vine^{-1}) for 17 h overnight DOY 233 to 234 and 16 h overnight DOY 234 to 235. (A) Power to the gauge heater (Q); (B) temperature difference between upstream and downstream thermopiles (ΔT); (C) sap flow and global irradiance (R_s). The gauge was operated under variable power control using an open-loop algorithm. Maximum allowable Q deliberately adjusted on DOY 233. Arrow in (A) denotes time at which program implemented the high-temperature "fail-safe" mechanism, reducing Q to 0.25Q for the remainder of DOY 234. Horizontal reference line in (B) is ΔT_{target}. Data were collected during 2003.

1999). The predetermined diurnal course of Q in an open-loop controller can lead to unaccounted-for heat storage by the stem during such midafternoon depressions in transpiration, with a larger error due to unmeasured Q_s as a water deficit intensifies.

The strength of the solar algorithm is the expectation that oscillations in F are not artifacts of instability in power control. An additional benefit is apparent stability under high rates of sap flow (Fig. 6). The daylength-based sine model also specifically accommodates the rapid diurnal changes in flow rates because its response time is set a priori: the time-derivative of sap flow is assumed to be proportional to that of the rate of change in irradiance at one's location. In the morning and evening, the rate of change of sap flow in deficit-irrigated Cabernet Sauvignon grapevines averaged 150 to 200 g h^{-1} per hour and in the well-watered Concord grapevines, it averaged 500 to 800 g

this period, the coefficient of variation in daytime ΔT was between 24 and 35%.

Because it is an open-loop, the solar algorithm may not be as well suited to maintain steady state under the substantial changes in daily maximum flow rates that can occur during rapid dry-down and rewetting cycles. In the Cabernet Sauvignon grapevines, sap flow deviated from an expected sinusoidal pattern from about solar noon until dusk (Fig. 5) at the dry end of each irrigation cycle, a pattern observed via measurements of gas exchange in the same vineyard (Perez Peña and Tarara, 2004) and elsewhere (Escalona et al., 2003; Ollat and Tandonnet,
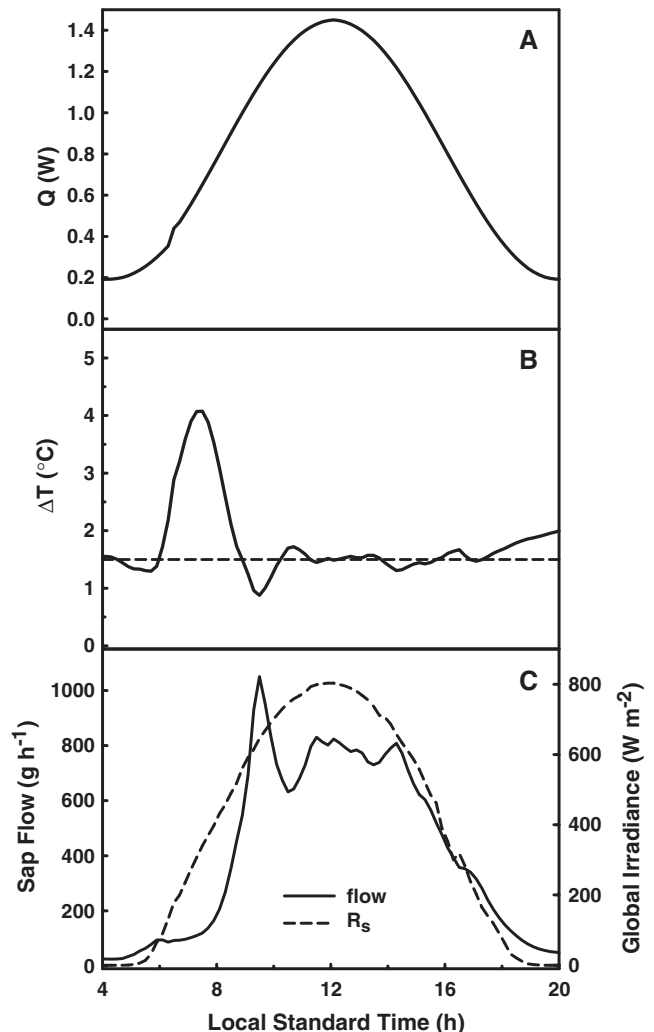

Fig. 6. Performance of a representative heat-balance sap flow gauge operated under variable power control using an open-loop algorithm. The gauge was on an 11-yr-old deficit-irrigated Cabernet Sauvignon vine in a semiarid environment. (A) Power to the gauge heater (Q); (B) temperature difference between upstream and downstream thermopiles (ΔT); (C) sap flow and global irradiance (R_s). Data were recorded on DOY 237, 2003. Horizontal reference line in (B) is ΔT_{target} (1.5°C).

h^{-1} per hour. The responsiveness of this power control algorithm over the diurnal time scale and its computational simplicity could make it attractive to many users.

On the few rainy or overcast days during the experiments, sap flow fell to 10 to 20% of its maximum rates as on days with clear skies. Regardless of power control algorithm, the program reliably decreased the power output to $0.25Q$ when ΔT exceeded the predetermined threshold (e.g., DOY 234; Fig. 5), which had been set high (10°C) so that measurements would not be interrupted by short-term (e.g., 2 h) anomalies. No trunk damage was observed on any vine due to the threshold ΔT. In regions where skies are more frequently overcast, one may prefer to maximize the amount of useable data by setting a default power "fail safe" above $0.25Q$.

Both algorithms that we tested performed identically at night, holding Q at Q_{min}, which maintained ΔT between 2 and 4°C (data not shown). Because nighttime flow rates were relatively stable ($\approx$25–50 g h^{-1}), Q_{min} was easy to monitor and adjust. Nighttime sap flow in grapevines may be a combination of transpiration and vessel refill due to root pressure (Fisher et al., 1997; Scholander et al., 1955), the sum of which would be detected by the sap flow gauge. In a potted Concord vine (trunk diameter 34 mm; leaf area 1–2 m^2), we measured nighttime water loss gravimetrically, confirming an average transpiration rate of 25 g h^{-1} that was detected by a sap flow gauge (data not shown).

Application Issues at High Flow Rates

We observed one troublesome phenomenon regardless of power control approach: an apparent loss of steady state for about 2 h every morning that caused a drop in the calculated value of F due to an anomalously large ΔT, followed soon thereafter by an artificially gross overestimate of sap flow due to a "crash" in ΔT to values well below 0.5°C (Fig. 1, 6). Neither power control algorithm was designed to accommodate such a dramatic change in the dead time of the system. It has been suggested (Grime et al., 1995a; Ham and Heilman, 1990; Shackel et al., 1992) that the initial spike in ΔT is caused by a heated volume or "plug" of xylem sap being in contact with the heater for an extended time early in the morning. An artificially high ΔT occurs as this volume of warm water begins to flow past the upper thermocouple, followed by a precipitous drop in ΔT as relatively cold water ascends from the root zone, after which the system returns to steady state. This phenomenon was observed in a potted apple tree (*Malus xdomestica* Borkh) with a trunk diameter similar to those of our grapevines and was reproduced under controlled conditions (Weibel and de Vos, 1994). The magnitude of this morning temperature anomaly is affected by the location of the thermocouples (surface-mounted vs. inserted; Ishida et al., 1991) and trunk anatomy as it influences the radial conduction of heat. Grapevines in particular can have actively conducting xylem across >75% of the cross-sectional area of a 20-yr old trunk (Tarara and Ferguson, 2001), approaching the "water-filled pipe" around which the heat balance theory of flow measurement was developed.

In many applications of the heat-balance sap flow method, the assumption of steady state is violated only at either end of the day, with resultant errors in F of similar magnitude but of opposite sign, described as "self-compensating" (Grime et al., 1995a). Thus, Q_s often is ignored with little consequence for the accuracy of cumulative estimates of sap flow, which appeared to be the case in well-watered Concord grapevines (Table 1). Measuring Q_s to improve instantaneous estimates of F, particularly in the morning, would be an ideal approach to the limitations of either of the power control algorithms that we tested, but doing so requires additional thermocouples or rewiring the gauges for measurements of absolute stem temperature rather than of ΔT. In practical terms, ignoring Q_s simplifies deployment of a multiple-gauge system, whereas the additional output signals required to include Q_s potentially decrease the number of gauges deployed per datalogger. This certainly is not technically prohibitive, but should be considered in the design of the experiment as one assesses datalogging and power resources, the degree of replication required, and the temporal scale at which accuracy is most important (i.e., instantaneous vs. cumulative estimates of sap flow).

To maximize replication in large field experiments or in cases of high plant-to-plant variability, one desires an efficient wiring design so that as many gauges as possible can be operated from a single datalogger; hence the scheme devised by Steinberg et al. (1990), followed by Senock and Ham (1993), and repeated here. Heat conducted radially and axially is included in the energy balance with this wiring scheme, although we have found that at high flow rates, Q_v can be negligible (<0.2% of Q) and Q_r quite small (Table 2). A stem heat balance without Q_r was justified under high flow rates in the understory of a tropical forest on the basis of negligible environmentally induced thermal gradients along the stem (Fichtner and Schulze, 1990). If it is critical to obtain accurate instantaneous estimates of daytime transpiration for plants with very high flow rates, one could modify gauges to achieve a compromise between minimizing or accounting for errors in F due to calculation of the stem energy balance, and maximizing the number of gauges. One clear advantage of the PD algorithm or any well-tuned feedback-loop approach to variable power

Table 1. Daily cumulative sap flow in well-watered grapevines ($n = 4$) estimated by the heat-balance method under constant power, with and without Q_s in Eq. [1]. To estimate Q_s, absolute stem temperature was measured by thermocouples inserted into the outer xylem. Q_s is heat stored by the stem segment.

	Cumulative sap flow		
DOY	Q_s assumed negligible	Q_s calculated	Difference
	L d^{-1} vine^{-1}		%
265	17.83	18.27	−2.5
266	18.64	19.49	−4.5
267	14.84	15.29	−3.0
268	19.54	19.78	−1.2
269	16.41	16.28	0.8
270	12.40	12.85	−3.6
271	10.69	10.70	−0.1
272	12.61	12.45	1.3
273	12.94	13.13	−1.5
274	13.22	13.49	−2.0

Table 2. Fraction of Q represented by Q_r and Q_v under conditions of high flow in cultivated grapevines for representative days with clear skies. Q_s assumed negligible. Concord grapevine was well watered (DOY 208, 2001). Deficit-irrigated Cabernet Sauvignon vines include the day before (dry; DOY 205, 2001) and the day after (wet; DOY 208, 2001) irrigation. Values are means of nine gauges. Average daily maximum flow rate (F_{max}) provided for reference. Heat balance sap flow gauges were operated in variable-power mode under an open-loop power control algorithm. Q is heat applied to the gauge; Q_r is radial heat flux by conduction; Q_v is axial heat flux by conduction, all in Watts.

Species	Period	Stem energy balance component		F_{max}
		Q_r	Q_v	
		— fraction of Q, % —		g h^{-1}
Concord grapevine	morning†	4.7	0.06	
	mid-day‡	1.8	0.01	2700
	evening§	2.1	<0.01	
	night¶	24.6	0.15	
Cabernet	morning	5.8	1.2	535
Sauvignon	mid-day	3.8	0.1	
grapevine (dry)	evening	12.8	1.2	
	night	32.6	7.1	
Cabernet	morning	5.8	1.1	1135
Sauvignon	mid-day	2.3	0.1	
grapevine (wet)	evening	11.3	1.4	
	night	29.9	7.3	

† 5.00 to 10.00 LST.
‡ 10.00 to 16.00 LST.
§ 16.00 to 21.00 LST.
¶ 21.00 to 5.00 LST.

control is in minimizing transient-induced errors due to Q_s, thus improving the accuracy of instantaneous estimates of F. The solar, or open-loop algorithm may share this advantage with the PD algorithm in areas where days with clear skies are frequent, but elsewhere, its use may require inclusion of Q_s in the stem heat balance.

CONCLUSIONS

The PD algorithm tested here requires tuning to minimize unwanted oscillation in Q. Generally, daytime ΔT was nearly constant except for a consistent 2-h period in the morning where Q, ΔT, and F appeared to be unstable, partly because the feedback loop was not tuned for the large time derivative of sap flow at that time of the day. A well-tuned PD algorithm for variable power control should obviate the need to measure Q_s by keeping the heated stem segment as close as possible to steady state. In practical terms, ignoring Q_s can simplify gauge wiring and make replication more efficient by maximizing the number of gauges per datalogger. The open-loop solar algorithm is attractive because of its computational simplicity. It worked well under clear skies, although there was a sinusoidal pattern to daytime ΔT with an amplitude of about 0.5 to 1.0°C. Under variable cloudiness or in situations where water deficits cause transpiration to deviate from a sinusoidal diurnal pattern, estimates of Q_s could be included in the calculation of the stem energy balance to yield more accurate instantaneous estimates of F under this open-loop controller. Both algorithms described here offer viable solutions to scientists with a working knowledge of dataloggers who are investigating high rates of sap flow in plants with stem diameters that are suitable to the application of the heat balance method.

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