CHAPTER

21

Sap Flow

We defined sap in the previous chapter (Chapter 20). Sap is the water in the tracheary cells of the xylem tissue. Measurement of the flow of sap through stems of plants to obtain accurate water-use data has long been a challenge for agronomists (Bloodworth et al., 1956). Two methods have been developed to measure sap flow (also called stem flow, even though the stem is not flowing): the heat-pulse method, an older method that has been in use since the time of Huber (1932) in Germany and the heat-balance method, a newer method that can be traced to Vieweg and Ziegler (1960) (Baker and van Bavel, 1987). The heat-pulse method is invasive and is often used on woody plants, such as orchard trees, and the heat-balance method is noninvasive and usually used on herbaceous plants. Herbaceous means "having the nature of a herb" and a herb is "any seed plant whose stem withers away to the ground after each season's growth, as distinguished from a tree or shrub whose woody stem lives from year to year" (Webster's New World Dictionary of the American Language, 1959). In this chapter, we consider these two methods. The heat-pulse and heat-balance methods, as well as other invasive and noninvasive methodologies to get water flow, have been reviewed by Escalona and Ribas-Carbó (2010).

21.1 HEAT-PULSE METHOD

With the heat-pulse method, flow is obtained from the time required for a heat input (the pulse) to travel from its source to a sensor up or down the stem. Measurements are in units of length per time (a velocity). This technique has been used on a variety of plants by researchers since Huber's (1932) pioneering work. The method is illustrated in Figure 21.1 on use in the stem of a kiwifruit vine (*Actinidia chinensis* Planch) (Clothier and Green, 1986). The method is used to schedule irrigations of water for kiwifruit grown in New Zealand. The widely spaced vines (5 × 5 m plant spacing) are grown on a trellis and often develop a full-cover leaf canopy.

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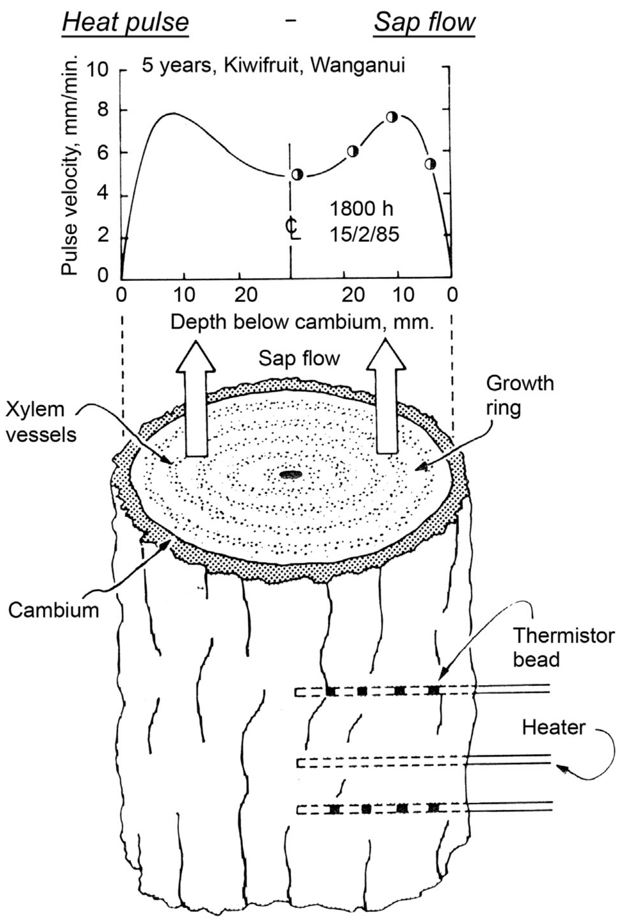

FIGURE 21.1 Heat-pulse method used to measure sap flow in a kiwifruit stem in Wanganui, New Zealand. Measurements are being taken at four different distances away from the cambium. In the graph in the upper part of the figure, the symbol that looks like the letter C with the letter L through it is the abbreviation used by engineers for "center line". *From Clothier and Green (1986). Reprinted by permission of the American Geophysical Union; John Wiley & Sons, Inc.; and Brent E. Clothier.*

The trellises are arranged in orchards surrounded by tall belts of shelter trees. The kiwifruit plant is unusual in that the water being lost by each individual vine through its massive leaf area (~100 m^2) must all travel up a 2 m length of a narrow vine (~50–100 mm diameter). The kiwifruit plant achieves this with a very high velocity of sap flow through the huge xylem vessels in its stem (up to 0.5 mm diameter and 200 mm length). These are arranged in an annular pattern of growth rings.

Heat is used as a tracer to infer the rate of vine water use. A brief pulse of heat (1−2 s) (Green et al., 2003) is supplied to the vine with a heater probe inserted radially into the stem. Thermistors (temperature sensors) placed asymmetrically on either side of the heater (one upstream and one downstream of the heater) measure the propagation of the heat wave (Figure 21.1). [A *thermistor thermometer* is a device for estimating the temperature based on a known relationship of its electrical resistance to temperature (Glickman, 2000, p. 770).] Equidirectional conduction of heat through the woody matrix and convection upward of heat in the moving sap lead to a characteristic pattern of temperature rise at both locations. The time delay for an equal temperature rise at both temperature sensors is recorded. The heat-pulse velocity can be related to the rate of sap movement and so, ultimately, to instantaneous plant water use. The radial pattern of heat flow through the vine can be obtained from paired thermistors placed through the stem.

The most widely used heat-pulse method is the *compensation* heat-pulse method (Edwards et al., 1996). It was originally conceived by Huber and Schmidt (1937). Because time is the primary measurement, the compensation method is robust and suited to field measurement. The time measured is the time required for a temperature difference between sensors to return to zero following a heat-pulse input (Edwards et al., 1996). In the USA, Bloodworth et al. (1955, 1956) were early users of this method and pointed out that Rein (1929) first used the method for studying the rate of flow in blood vessels.

In the method, the temperature rise following the release of a pulse of heat is measured at distances Xu upstream and Xd downstream from the heater (Green and Clothier, 1988). Heat-pulse velocity, V (in units of length/time), is calculated from

$$V = [(\mathrm{Xu} + \mathrm{Xd})/2t], \tag{21.1}$$

where t is the time delay for the temperatures at points Xu and Xd to become equal. If the sap and woody matrix are considered to form a homogeneous medium, then sap flux density, J (in units such as cubic meter per squared meter per second or meters per second), can be calculated from

$$J = P(0.33 + M)\cdot V, \tag{21.2}$$

where P is the wood density (oven dry weight of wood/green volume, in units such as kilogram per cubic meter) and M is the moisture content [(wet weight − oven dry weight)/(oven dry weight)] of the sapwood. (We define sapwood in the next paragraph.) The units in the numerator and denominator for M cancel, so M can be considered to be a pure number, which then can be added to 0.33 in Eqn (21.2). The kilogram in the numerator of P can be changed to cubic meter assuming that the density of water is 1 g/cm^3, which then gives units of J in length/time, such as meter per second.

Sap velocity varies with depth into the stem. To calculate volumetric flow rates, sap flux density is measured at different distances away from the cambium, such as shown in Figure 21.1, where it is measured at four different distances. [Remember the *vascular cambium* is a meristem (a tissue that divides to make new cells), which produces phloem on the outside and xylem (wood) on the inside. See Figure 17.3 for the location of the vascular cambium. It is present in stems that undergo secondary growth.] A second-order least squares regression equation is fitted to the sap flux density measurements. The resulting flux profile is then integrated over the sapwood cross-section to calculate the volume flux Q (in units such as cubic decimeter per day) (Green and Clothier, 1988, 1995)

$$Q = 2\pi \int_H^R rJ(r)\mathrm{d}r, \tag{21.3}$$

where $J(r)$ is the sap flux at radial depth r in a stem of cambium radius R and heartwood radius H. Esau (1977, pp. 511–512) defines the *heartwood* as the inner layers of secondary xylem that have ceased to function in conduction. It is generally darker colored than the functioning sapwood. Esau (1977, p. 524) defines the *sapwood* as the outer part of the wood that contains living cells and in which conduction of water takes place. It is generally lighter colored than the heartwood (Esau, 1977, pp. 511–512 and 524).

Equation 21.2 underestimates sap flow. This is a result of blockage of the flow by the probes placed in the sapwood. A correction to Eqn (21.2) needs to be calculated that depends on the wound width. The theoretically derived correction factor is then used to correct the heat-pulse measurements for probe-induced effects of wounding. Without such a correction, the heat-pulse measurements of sap flow are typically low by a factor of ≥50% (Green and Clothier, 1988; Green et al., 2003).

The accuracy of the heat-pulse measurements has been checked by comparing them with independent measurements of sap flow. A kiwifruit vine (*Actinidia deliciosa*) and an apple tree (*Malus sylvestris* × Red Delicious) each were cut off at the ground level and the ends placed in a container of water. The drop in water level was measured, while simultaneous heat-pulse measurements were made. The heat-pulse measurements showed a good agreement with the physical measurement of the quantity of water imbibed from the container (Green and Clothier, 1988). Figure 21.2 shows the heat-pulse method in use on an apple tree in the field. Note in Figures 21.1 and 21.2 the asymmetrical placement of the

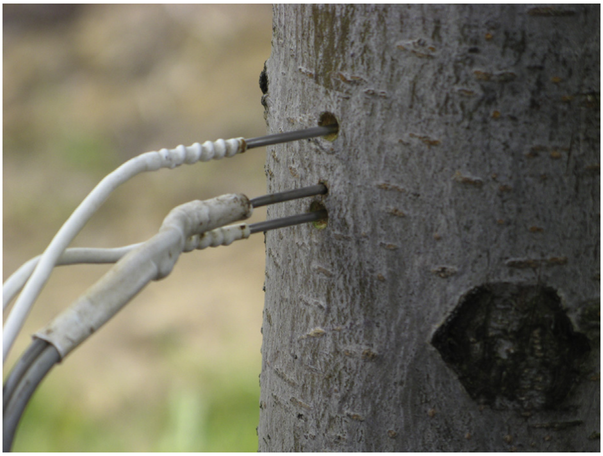

FIGURE 21.2 The heat-pulse method in use on an apple tree. *Photograph courtesy of Steven R. Green, The New Zealand Institute for Plant and Food Research, Ltd., Palmerston North, New Zealand.* (For color version of this figure, the reader is referred to the online version of this book.)

thermistors on either side of the heater. In Figure 21.2, the heater is the middle probe.

An alternative method to the compensation heat-pulse method was developed by Cohen et al. (1981) and is called the *T-max* heat-pulse method (Green et al., 2003). It relies on measuring the time for the maximum temperature rise to be recorded by a single sensor located a distance downstream from a line heater. The theory for the method is reviewed by Green et al. (2003), who also give correction factors for both the compensation and T-max heat-pulse methods. The correction factors were confirmed by comparing heat-pulse measurements in the trunk of a willow (*Salix alba* L.) and a poplar (*Populus deltoides* W. Bartram ex. Marsh), against the actual rates of transpiration determined from measured weight loss of the trees growing in large lysimeters. On a daily basis, both heat-pulse measurements were found to be within 5–10% of the actual transpiration. The compensation method accurately measured flows close to 2 cm/h. The T-max method had difficulty in resolving any flows slower than about 10 cm/h.

The heat-pulse technique has several advantages. It can be used to measure sap flow in tree stems with minimal disruption to the sap stream. The measurements are reliable and accurate, use relatively simple and inexpensive instrumentation, provide a good time resolution of sap flow, and are well suited to automatic data collection and storage (Green et al., 2003). Sequential or simultaneous measurements on numerous trees are possible. This permits the estimation of transpiration losses from whole stands of trees. Other advantages of the method are the following: (1) one can get flow at different depths into the stem; probes can be inserted into the stem from 0.5 to 4 in (13–102 mm); (2) one can measure sap flow in thick stems (trees); (3) measurements are fast; and (4) roots can be measured, if they are woody. Clothier and Green (1992) and Green and Clothier (1995) were the first to obtain measurements of sap flow in roots (Figure 21.3). They used the heat-pulse technique to monitor sap flow in the stem and several large roots of kiwifruit vines to see how the flow of water in roots responded with local changes in soil water availability. They found that inactive roots in dry soil were able to recover their activity quickly when irrigated. In 2013, a miniature sap-flow sensor using

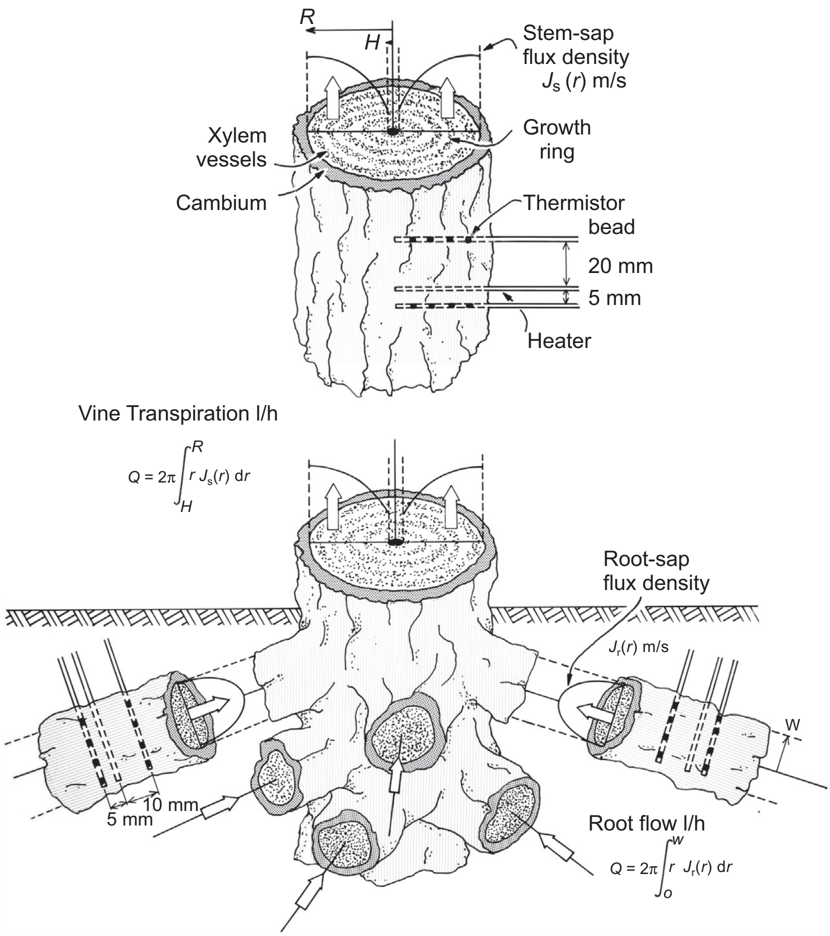

FIGURE 21.3 A schematic diagram of the arrangement of the heat-pulse sensors in the stem and two probed roots of a kiwifruit vine. For abbreviations, see the text. *From Clothier and Green (1992). Reprinted by permission of Brent E. Clothier.*

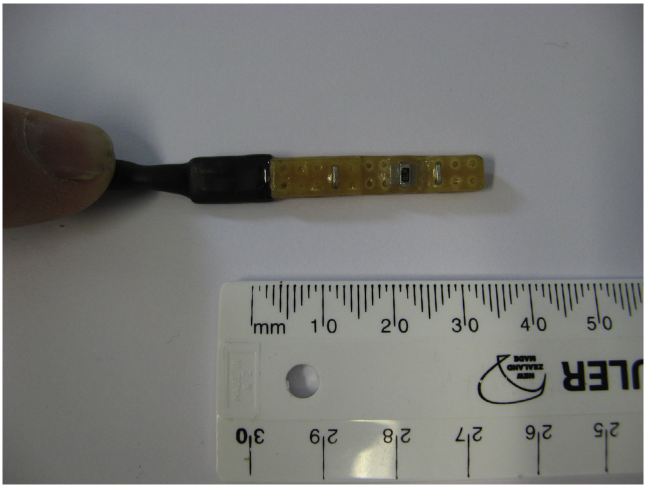

FIGURE 21.4 Miniature sap-flow sensor that uses the heat-pulse method. *Photograph courtesy of Steven R. Green, The New Zealand Institute for Plant and Food Research, Ltd., Palmerston North, New Zealand.* (For color version of this figure, the reader is referred to the online version of this book.)

the heat-pulse method became available from Tranzflo NZ, Ltd, Palmerston North, New Zealand (Figure 21.4).

The disadvantages of the heat-pulse technique are that (1) it is an invasive technique and a small amount of xylem tissue is damaged by the probes; and (2) one needs to adjust readings for the area of the probes. Also, there has been confusion about the terminology used in the heat-pulse method, and different units are used (e.g., cm h^{-1}, cm^3 s^{-1} cm^{-2}; 10^{-3} kg $m^{-1}s^{-1}$) (Edwards et al., 1996). Reports on the heat-balance method, which we now turn to, have been more consistent, because of the simplicity of the underlying theory (Edwards et al., 1996).

21.2 HEAT-BALANCE METHOD

The heat-balance method is ideal for thin-stemmed, barkless species such as herbaceous plants. In the heat-balance method, flow is obtained by balancing heat fluxes into and out of the stem. The units of the heat-balance method are mass per unit time. Note that the units of the heat-pulse method (usually expressed as length/time) and heat-balance method (mass/time) are fundamentally different and cannot be compared directly.

There are two approaches for the heat-balance method. In one approach, used for trees, heat input to a segment of the trunk (stem) is automatically and continuously adjusted to maintain a constant temperature difference between the heated segment and unheated trunk (stem) below. As sap flow changes (transpiration changes), the required heat input must also change in order to provide the basis for stem-flow measurements (Baker and van Bavel, 1987).

Another approach is used for herbaceous plants, and it is the constant-heating method. This method was developed by Sakuratani (1981, 1984) in Japan. In this approach, the heat input from an external annular (round) heater is kept constant and fluxes of heat out of the system are calculated from measured temperature gradients, enabling direct calculation of the mass flow rate of water in the stem. Stem-flow gauges, called Dynagages, made by Dynamax (Houston, Texas), are based on this method. They won the Agricultural Engineering Society's 1989 award for outstanding innovations in product technology (Ploskonka, 1990). The President of Dynamax is Michael van Bavel, the son of C.H.M. van Bavel, who helped to design the stem-flow gauges. (For a biography of C.H.M. van Bavel, see the Appendix, Section 21.3.) In this section, we shall focus on theory of these gauges, and we follow the analysis of Baker and van Bavel (1987).

Figure 21.5 shows the physical situation. A flexible heater, 10 mm in length, is wrapped around a segment of a stem, and it provides a small, steady, known amount of heat. Foam insulation, with a thermal conductivity much lower than that of the plant tissue, encloses the

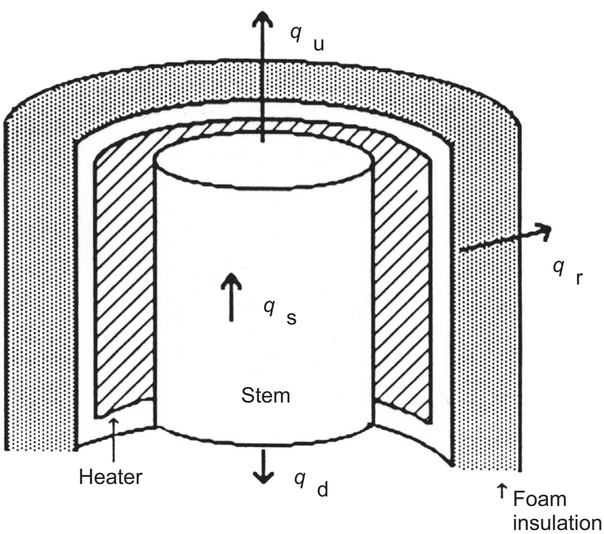

FIGURE 21.5 Heat balance of the heated stem segment using the heat-balance method. It is a schematic diagram, not drawn to scale. The length of the heater is 10 mm. The thickness of the insulation is 12 mm and its length is 50 mm. Symbols refer to Eqns (21.4–21.6); q_s is the rate of heat transport by the sap stream, given by F in Eqn (21.8). *From Baker and van Bavel (1987). This material is used by permission of Wiley-Blackwell and John M. Baker.*

heated segment and extends for several centimeters both above and below the heated segment. Heat then moves by conduction upward, downward, or in the radial direction, and from these heat fluxes, the rate of heat transported on a mass basis by the sap stream can be calculated.

Now, let us look at each of these heat flows.

21.2.1 Heat Up

The conductive heat upward (q_u, in units of watts) can be calculated with Fourier's law for a one-dimensional heat flow. (Fourier's law is a linear flow law, and we presented it in Chapter 7 in Table 7.1.)

$$q_u = k_{st} A(\mathrm{d}T/\mathrm{d}X), \tag{21.4}$$

where

k_{st} = the thermal conductivity of the stem tissue (W/m/K) (remember a watt is a joule per second and a watt is a unit of power; power = work/time),

A = the cross-sectional area of the stem (m^2),

$\mathrm{d}T/\mathrm{d}X$ = temperature gradient (K/m),

$\mathrm{d}T/\mathrm{d}X$ is obtained from the output of two differentially wired thermojunctions (thermocouples) which are 3 mm apart and in direct contact with the stem, the lower of the two being immediately above the heater. We assume (due to insulation) that the gradient of temperature is uniform over the cross-section.

21.2.2 Heat Down

Another pair of thermojunctions is located below the heater and allows the determination of the conductive flux downward, q_d, in units of watts:

$$q_d = k_{st} A(\mathrm{d}T/\mathrm{d}X), \tag{21.5}$$

where k_{st}, A, and $\mathrm{d}T/\mathrm{d}X$ have been defined for Eqn (21.4).

In the equations for upward and downward flux, the value of A must be known from an actual measurement, and the value of k_{st} (thermal conductivity of stem) is taken to be 0.54 W/(m K), a value that is the average of measured values for herbaceous species, and is slightly less than that of water. From Table 3.1, we see that water at 20 °C has a thermal conductivity of 0.00144 cal/cm/s/°C. We can convert 0.54 W/m/K to units of calories per centimeter per second per degree as follows knowing from Chapter 2 that 1 cal = 4.184 J and 1 W = 1 J/s, so 1 W = 0.239 cal/s (Schaum, 1961, p. 153):

[0.54 W/(m K)] (0.239 cal/s/W) (1 m/100 cm) = 0.0012906 cal/cm/s/K.

We note that this is a correct conversion, even though Table 3.1 has degrees centigrade for thermal conductivity and we are using degrees Kelvin in the analysis of the theory for the heat-balance method. Lide (1994) gives the conversion on pp. 1–38. He says that, to convert watts per meter per Kelvin to calories per centimeter per second per degrees centigrade, we multiply by 0.00239006. This is what we have done in the above conversion.

This value, 0.0012906 cal/cm/s/k for the thermal conductivity of the stem, is not much different from 0.00144 cal/cm/s/K. So we can accept the assumption that the thermal conductivity for herbaceous species is slightly less than that of water.

21.2.3 Radial Flow

The radial outward flow of heat is calculated from the voltage output of a thermopile composed of eight thermojunctions (thermocouples) in series located on either side of a 2-mm cork sheath between the heater and the foam insulation. A *thermopile* is an instrument consisting of a series of thermocouples, used for measuring minute changes in temperature or for generating thermoelectric current (Webster's New World Dictionary of the American Language, 1959). The flux is approximated by Eqn (21.6), the integrated form of the equation for radial heat flow (q_r, in units of watts) in a cylinder of infinite length (Carlslaw and Jaeger, 1959).

$$q_r = 2\pi k_{co} L (T_i - T_o)/\ln(r_i/r_o), \tag{21.6}$$

where
k_{co} = the thermal conductivity of cork (W/m/K),
L = length of the heated segment (m),
T_i = temperature at the inner surface of the cork sheath (K),
T_o = temperature at the outer surface of the cork sheath (K),
r_i = the radius of the inner surface of the cork sheath (m),
r_o = radius of the outer surface of the cork sheath (m).

All parameters in Eqn (21.6) (π, k_{co}, L, T_i, T_o, r_i, r_o) are constant and can be combined giving us Eqn (21.7), below. The conversion factor relates the thermopile output (E) to the temperature difference ($T_i - T_o$), and one gets a simple sheath "conductance", K_{sh}, with the units of watts per voltage output (W/V_o, the subscript signifies voltage output from the thermopile), so that Eqn (21.6) may be rewritten:

$$q_r = K_{sh} E, \tag{21.7}$$

where
K_{sh} = sheath conductance (W/V_o),
E = voltage output from thermopile (V_o).

Subtraction of the three fluxes (up, down, and radially) from the known heat input gives the heat transported by the sap stream. To calculate the mass flow rate (grams per second) of water from the sap heat transport, it is necessary to know the temperature difference between the water entering and leaving the heated portion of the stem. To obtain this value, the upper thermojunction nearest the heater is differentially wired to the lower junction nearest the heater. Again, the assumption of radial thermal homogeneity is made. The temperature difference, multiplied by the heat capacity of water (not that of the stem), is divided into the sap heat transport, yielding the mass flow rate of the sap itself.

$$F = \left(P - q_{\mathrm{u}} - q_{\mathrm{d}} - q_{\mathrm{r}}\right) / \left[C_{\mathrm{p}}(T_{\mathrm{out}} - T_{\mathrm{in}})\right], \tag{21.8}$$

where

F = sap-flow rate (g/s),

P = power input to the heater (W),

C_{p} = heat capacity of the xylem sap (J/g/K),

T_{out} = temperature of the junction above the heater (K),

T_{in} = temperature of the junction below the heater (K), and q_{u}, q_{d}, and q_{r} are as defined above, all in units of watts.

Figure 21.5 shows F as q_{s}, the rate of heat transport by the sap stream with units of grams per second. The value K_{sh}, required in Eqn (21.7) ($q_{\mathrm{r}} = K_{\mathrm{sh}}E$), is calculated from Eqn (21.8) by setting $F = 0$ and making measurements on a stem that has been excised and sealed with vaseline to ensure that the sap-flow rate is zero. This is a zero-set procedure, not to be confused with a calibration. If $F = 0$, we can solve for q_{r} and then put q_{r} in Eqn (21.7) and solve for K_{sh}.

In the method, we are assuming that the heat capacity of the xylem sap is the heat capacity of water. We also are assuming that the thermal conductivity of the stem is the same for all herbaceous plants. We are assuming that most heat is transported by the xylem. Also, we are assuming the whole cross-section is heated uniformly across the stem. The method is absolute, not transient, and it needs no calibration.

The heat-balance method has the advantages of providing direct, accurate, fast, and noninvasive measurements of sap flow in stems of plants. No calibration is required. Like the heat-pulse method, not only can the sap-flow rate of individual plants be determined, but also the transpiration rate of an entire field can be determined with the heat-balance method. Ham et al. (1990) used heat-balance gauges to determine near-instantaneous measurements of transpiration of cotton (*Gossypium hirsutum* L.) in Lubbock, Texas. Transpiration on a unit land area basis was calculated by normalizing stem-flow measurements by leaf area or plant density. However, the heat-balance method does have the disadvantage of overestimating high flow rates. To correct this problem, one can use larger heaters (20 mm instead of 10 mm). The method also requires a minimum diameter of a stem, but sensors have been miniaturized so that stems 2 mm in diameter can be measured. The method cannot be used on roots, as can the heat-pulse method.

The heat-balance method also cannot measure low flow rates. The gauge has a good accuracy when sap-flow rates are ≥20 g/h (Zhang and Kirkham, 1995). Sap flow in both dicotyledonous (dicots) and monocotyledonous (monocots) plants can be measured with the heat-balance method, even though they differ in stem anatomy. Dicots usually have the xylem tissue oriented in a cylinder (in cross-section) around a central pith of the stem, while monocots have vascular bundles that are scattered across a stem. (See Chapter 17, Section 17.1, for the difference in stem anatomy between dicots and monocots.) The conducting cylinder of dicots, therefore, is close to the heat of the gauge. Zhang and Kirkham (1995) found that the heat-balance method could be used on monocots and dicots. The limiting factor was the sap-flow rate. The monocot in their study [*Sorghum bicolor* (L.) Moench] had a low sap-flow rate even under well watered conditions (<18.9 g/h). The well watered sunflower (*Helianthus annuus* L.), a dicot under the same conditions, had a sap-flow rate of 64.7 g/h. However, this sap-flow rate was less than sap-flow rates for woody plants under field conditions, which are often >100 g/h. Zhang and Kirkham (1995) concluded that sap-flow rate is more important than stem anatomy in determining the accuracy of the heat-balance gauge.

21.3 APPENDIX: BIOGRAPHY OF C.H.M. VAN BAVEL

Cornelius H.M. van Bavel, a pioneer in the study of the soil–plant–atmosphere continuum using experimental and simulation methods, was born on September 15, 1921, in Ginneken, a small town just south of Breda, The Netherlands. In September 1938, he entered Wageningen Agricultural College (now University), where he obtained an engineering degree (Ir.) in horticulture in October 1945 (Brown, 1988; van Bavel, 2008), following a turbulent and stressful five years of Nazi occupation (van Bavel, 2000a). During World War II, he distributed underground papers and met with other individual opponents of the German occupiers. He helped to prepare false identity papers and provide money or food for individuals in hiding, who had escaped from concentration camps. They got around by train or bicycle. The work was risky, and there was a continuous battle in the air, and he very nearly lost his life a couple of times (C.H.M. van Bavel, personal communication, May 8, 2011). Wageningen Agricultural College was closed in 1943 by the German authorities (van Bavel, 2008), and the students were ordered to report for work in Germany. That was even more dangerous, but he, with many others, ignored this command and he was able to survive. Some of his professors also were active in the resistance movement and had to leave their homes and go into hiding (van Bavel, 2008).

Supported by a generous grant from The Netherlands-America Foundation, he was able to come to the USA and entered Iowa State College (now University) in January 1946, and received his master's degree in soil physics under the direction of Don Kirkham in December 1946. On May 27, 1947, he married, in The Netherlands, Margaret Lips, whom he became engaged to while in the war-torn Netherlands. She is an artist specializing in jewelry work (van Bavel, 2008). He was an agronomic consultant in La Paz, Bolivia, in 1947, and he reentered Iowa State College in February 1948, and obtained a Ph.D. degree in soil physics under Don Kirkham in December 1949. For his Ph.D. research, he investigated the stability of soil aggregates and means for increasing aggregation. He has a patent, dated May 28, 1957, and entitled "Soil stabilizer and soil treated thereby" (USA Patent No. 2,793,960) resulting from this research. At Iowa State, he also worked with Kirkham on developing an electrical analog of the auger-hole method for measuring soil permeability. He also explored the possibilities of numerical simulation for solving problems, an area that he became more interested in, when electronic computers became available about 15 years after he left Iowa State (van Bavel, 2000a).

After receiving his Ph.D., van Bavel was an Associate Professor of Agronomy at North Carolina State University in Raleigh. There he studied the energy balance of a transpiring plant surface and how its water use could be derived from meteorological data. Howard Penman in England had collected data on the water use by turf, from which he formulated the famous Penman equation in 1948. (See the Appendix of Chapter 28 for a biography of Penman.) A visit by Penman to Raleigh in 1951 was the prelude for a number of measurements in the North Carolina environment of evapotranspiration that van Bavel made (van Bavel, 2008). Van Bavel was instrumental in undertaking analysis of regional drought incidence in the Southeastern states (American Society of Agronomy, 1964). In Raleigh, he studied the limits to plant growth when oxygen and water were insufficiently available to the root system. He also investigated the practical implementation of the neutron scattering method for measuring soil moisture as well as a similar method to measure soil density with gamma radiation (van Bavel, 2008).

In September 1958, he moved to the new US Water Conservation Laboratory in Tempe, Arizona, where he was Chief Physicist. There, he instigated an intensive study of evapotranspiration and related soil and climatic processes (American Society of Agronomy, 1964). He invented, along with two colleagues, the first leaf resistance meter, called a porometer. The paper describing the porometer (van Bavel et al., 1965) is a citation classic (Institute for Scientific Information, 1983). It became the basis for a commercial model made by Li-Cor, Inc., Lincoln, Nebraska, which is no longer manufactured by Li-Cor. However, the porometer is marketed by Delta-T Devices in England. It uses the transient method of measurement and the use of porous plates for its calibration. (See Chapter 24 for a description of porometers.) Also at Tempe, he developed with Ray Jackson a desert survival kit (Jackson and van Bavel, 1965). (See the Appendix of Chapter 26 for a biography of Jackson.) The kit, called a solar survival still, was awarded a US patent.

Missing the opportunity to work with students, he decided to move in 1967 to Texas A&M University in College Station, where he was Professor in the Department of Soil and Crop Sciences. There he was influenced by the publications of C.T. de Wit and his students in Wageningen and started to focus on computer-assisted numerical modeling. He also codirected a University-wide program involving cogeneration of energy, desalination of irrigation water, and food production (Council for Agricultural Science and Technology, 1986). At Texas A&M, he coinvented a fluid roof solar greenhouse and developed design principles of controlled environmental facilities and of commercial greenhouses (American Society of Agronomy, 1987). While in Texas, he and his family were active citizens, not only in local environmental politics but also in trying to practice what they preached. They traveled by bicycles, used a compact car, and installed a solar water heating system in their home (van Bavel, 2008).

In 1983, van Bavel accidentally discovered an obscure description of a method done in Japan for attaching a sap-flow meter to the stem of a plant and using it to monitor the rate of transpiration. This was the basis for the work that he and his student, John Baker, did with sap-flow gauges (Baker and van Bavel, 1987). They were responsible for the design and first tests of a robust, constant heat stem-flow gauge that was suitable for field work. From this work, it was a logical step to develop it commercially, which was done in 1986 by Dynamax, Inc., a company started by his son, Michael van Bavel. Everyone now in the plant–water relation field is familiar with the method and hundreds of gauges are in use over the entire world (van Bavel, 2008).

Van Bavel worked on temporary duty at the University of California in Riverside in 1963, the Center for Ecophysiological Studies in Montpellier, France, in 1973 (American Society of Agronomy, 1987), the University of Reading in England, and the Hokuriku Agricultural Experiment Station in Joetsu, Japan (van Bavel, 2008).

His accomplishments were recognized in 1958 when he was awarded the United States Department of Agriculture Superior Service Award (American Society of Agronomy, 1964). He is Fellow of the American Society of Agronomy (1963) and Soil Science Society of America (SSSA)

(1963). He received the SSSA Soil Science Award (1985) (American Society of Agronomy, 1987) and the Faculty Distinguished Achievement Award in research in 1986 from Texas A&M University (Fette, 1986).

Van Bavel retired on January 31, 1987, after 19 years of service at Texas A&M University (American Society of Agronomy, 1987). In retirement, he and his wife have traveled widely around the world. He also has translated three books written in Dutch by Hugo de Vries (1848–1935) during three long journeys to the USA in 1904, 1906, and 1912 (van Bavel, 2000b). De Vries was a famous Dutch botanist known for his studies on mutation (Benton, 1971). The three travel books contain detailed impressions obtained by a European plant scientist (de Vries) of the emerging institutes of higher learning in the US, the agricultural experiment stations, the land grant colleges, and the programs of the US Department of Agriculture.

He and Margaret, who have five sons, three daughters, and 11 grandchildren, reside in Kerrville, Texas, where two of their sons live.

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