

Methods to Estimate Sap Flow

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A variety of methods is available to calculate mass flow of water in the transpiration stream by using heat as a tracer. Measurements can be taken both in herbaceous and woody plants and in any conductive organ, including roots. Depending on the method, measurements are taken in the part of the conductive organ where the sensors are located, or in the whole perimeter of the conductive organ. Some methods integrate the sap flow in the whole sapwood, while others give information to calculate sap flow at different depths below the cambium. Some methods are invasive, since the sensors are located within the sapwood; others are non invasive, being the sensors located outside, although in close contact, of the conductive organ. Some methods are suitable for stems of small diameters, while others can be used in large trees. Calibration is convenient in all cases, being compulsory for the invasive methods, since the insertion of the probes alters the xylem characteristics. Some methods measure continuously, while others measure discontinuously. Some cannot measure below a threshold of heat velocity, while others are useful for measuring very low sap flow values, even those occurring during reverse flow. The user, therefore, must be aware of the potential and limitations of the different available methods before choosing the most suitable for his/her purposes. Below we mention the existing methods for estimating sap flow from heat measurements, together with references to key papers where details on the fundamentals and performance of each method are given (see also review papers by Campbell 1991, Swanson 1994, Cermak 1995, Smith and Allen 1996, Kostner et al., 1998, Cermak and Nadezhdina 1998, and others cited in the “Key papers” Section).

Heat Balance with external heating, or stem heat balance (SHB) method

Vieweg and Ziegler (1960) developed a method where a heater band is wrapped around the conductive organ. A small quantity of heat is applied continuously to increase the temperature of the enclosed stem to a certain level above the non heated parts below. Daum (1967) was the first who developed a quantitative stem heat balance method. This was based on heat flow plates measuring natural heating of stems from surrounding, therefore not requiring any special source of energy. Similar principle was applied by Sakuratani (1981), but applying the artificial heating. This approach was later improved e.g., by Sakuratani (1981), by Valancogne and Nasr (1989) and by Weibel and Vos (1994). Further versions have been developed by Baker and Van Bavel (1987), Steinberg et al. (1990), Ishida et al. (1991), Senock and Ham (1993) and Chandra et al. (1994), among others. All these methods are based on the calculation of an energy budget between the energy put into the stem and the energy losses. Those are calculated from temperature measurements made on top of or just under the bark. Actually, the stem heat balance gauge comprises a partially flexible heater, a few centimetres in width, which is wrapped around the stem and enclosed in layers of insulating and weather-proof materials. Heat is applied to the entire circumference of the stem encircled by the heater and the mass flow of sap obtained from the balance of the fluxes of heat into and out of the heated section of stem. The SHB method is suitable both for

herbaceous and woody plants. However, sensors are hard, of fixed size and do not allow stem growth, therefore their positions must be frequently changed in long-term studies to prevent stem strangulation. In large stem sizes both the heater band and the energy requirements becomes too large, and the calculation of the stored heat term becomes difficult. In fact, these methods have been mostly used for stem diameters smaller than 10-12 cm. The SHB system is available from Dynamax Inc, EMS Brno and ICT International (see Manufactures' Directory).

Heat Balance with Internal Heating, or the trunk sector heat balance method (THB)

This is a heat balance for stem segments, developed by Čermák et al. (1973, 2004) and Kučera et al. (1977), mathematically supported by Tatarinov et al. (2005). It consists of three to five stainless steel metal plates inserted parallel into the sapwood, at a distance of two centimetres. These plates are used as electrical poles of the heater. They should approximately cover the whole sapwood depth, than the flow is integrated over the sapwood. An AC voltage source is connected to the plates and the current running through the wood between the plates results in even heating between the plates. Similarly to the heat balance, the temperature difference between heated and non-heated stem segments installed in two depths below cambium and power supply is measured and used to calculate mass flow. The power can be constant, but more recent version of the method has the advantage of keeping a constant temperature difference system by variable and recorded power thus also keeping the same temperature gradients and avoiding overheating of the segment in which it is located. Minimum heat losses from the heated stem part (visible on the records as the so called fictitious flow) are subtracted from the recorded data to get the true flow values. The same principle, but with external heating is applied also for shoots or small roots (Čermák et al. 1984, Lindroth et al. 1995, later highly improved by EMS). The corresponding sensors are soft and completely flexible, allowing the shoots to grow up to doubling their diameters. The THB system is available from EMS Brno and ICT International (see Manufactures' Directory)

The heat dissipation (HD) method

The method based on the heated probe technology, developed by Viewegh and Ziegler (1960), independently also by Ittner (1967), Balek and Pavlik (1977) and better quantified by Granier (1985). It is based on the detection of convective heat transport (heat carried with the sap stream). Usually two thermocouples are mounted in thin needles, one on each. The needles are inserted radially in the sapwood above each other about 10 cm apart. The upper sensor is heated with constant power and the sap flow velocity is calculated from the temperature difference between the two needles. This background information goes into the equation using an empirical coefficient, being applied for all species, according which the sap flow density is calculated. The maximum temperature difference occurs under no flow conditions, and decreases with increasing sap flow velocity. The system measures flow along a short part of sapwood depth, only more such sensors installed in different depths (but always within the conducting xylem) can provide values valid for the whole sapwood depth. The HD

system is available from Dynamax Inc, EKOMATIK and ICT International and UP-GmbH (see Manufactures' Directory)

The Heat Field Deformation method (HFD)

This method, developed by Nadezhdina et al. (1998), is based on the analysis of temperature differences around a linear heater inserted in the sapwood. These temperature differences characterise the deformation of the heat field around the heater caused by the ascent of sap. The HFD method can measure wide size of trees in a wide scale of flow rates including low, zero and reverse flows. The HFD sensors consists of a linear heater and two pairs of differential thermocouples (symmetrical and asymmetrical) measuring the temperature difference in axial (dT_{sym}) and tangential (dT_{asym}) directions around the heater (Nadezhdina et al., 2002) as raw data. Sap flow is then calculated from the mentioned temperature differences. The multi-point sensor has several thermocouples along each needle and allows measurements of sap flow radial profile. dT_{sym} is also known as the sap flow index (SFI) which can be used as a stress indicator (Nadezddina, 1999). The HFD system is available from ICT International (see Manufactures' Directory)

The Cohen's heat-pulse method, or T-max method

The first reference to a heat pulse methods is that of Huber (1932). This system was based on two probes, one containing a heater and the other a temperature sensor. The time for the first appearance of heat at the sensor was assumed to be the same as the time taken for the sap to move this distance. Huber recognized the importance of distinguishing between the effect of convection by the moving sap and the transport of heat by thermal conduction. To separate these two effects, Huber and Schmidt (1937) developed an early version of the 'compensation' heat-pulse (CHP) method in which one sensor was downstream and the other sensor was upstream of the heater. The time of peak warming of the upstream sensor compared to the downstream one, was used to 'compensate' for the effects of thermal conduction. Later, Marshall (1958) proposed a new probe arrangement and developed a theoretical framework for the compensation heat pulse method. His analytical theory, was used by Cohen et al. (1981) to develop his heat pulse method, known as the T-max method. This method measures simultaneously the heat wave at several depths in the trunk using six-thermistor probe spaced 8 mm apart. The probe is inserted at a distance of 15 mm downstream of a line source heater and records the time delay for a maximum temperature rise at the sensor location. A second probe, with a single thermistor is located at a distance 20 mm or more upstream of the heater where the temperature is not affected by the heat wave. This probe is used to compensate temperature changes of the trunk during the day.

The Green's HPV system

The heat-pulse velocity (HPV) system developed by Green (1998) is based on the CHP method (Swanson and Whitfield, 1981) The HPV system can be used either for the compensation method or for the T-max method (Green et al., 2003). For the compensation method, two temperature probes are placed asymmetrically on either side

of a line heater that is inserted radially into the sapwood. Each temperature probe has several thermocouples at different depths from the cambium. Following the application of a brief 1-to 2-s heat pulse, the time delay for an equal temperature rise at the two sensors placed at the same depth below the cambium, upstream and downstream the heater, is used to calculate a heat pulse velocity. A theoretically derived correction factor is then used to correct the heat pulse measurements for any probe-induced effects of wounding and to calculate volumetric rates of sap flow. For the T-max method, the upstream probe is simply shifted to a distance of 40 mm from the heater so that it does not sense the heat pulse. Rather, this second reference probe is used to compensate for any background changes in stem temperature that may occur during the T-max measurement. Once again, correction factors are needed to derive actual sap flow values from the recorded T-max values. The HPV system is available from Advanced Measurements and Controls Inc and Tranzflo NZ Ltd (see Manufacturer' Directory).

The Calibrated Average Gradient (CAG) method. Testi and Villalobos (2009) developed the CAG method to calculate low sap velocities from sap flow records taken with the standard CHP/HPV method. The temperature sensing probes are placed at different distances upstream and downstream from the heater (typically 5 and 10 mm, respectively). While measuring the temperature difference (above-below) and searching for the time delay needed to have the same ΔT as before the pulse, the ΔT readings are averaged (ΔT_a) over the same amount of time (180 s or more). The relationship between ΔT_a and the heat pulse velocity (the last measured with the traditional method, when the velocity is large enough for this to be applied) is linear for low velocities down to zero and below. This linear function, $v_h = f(\Delta T_a)$, is obtained by regression, and it is used to calculate the pulse velocity when it is too low to be detected by the traditional method. The parameters of the linear function are specific for any probe-wood match (so they are to be empirically determined whenever a probe is installed), but are constant with time if the thermal characteristics of the system don't change. The CAG method is available from Puech & Asociados (see Manufacturer' Directory).

The heat ratio method (HRM)

The methods by Cohen and Green are of limited value for measuring low rates of flow (Becker, 1998). The heat ratio method (HRM) is a heat-pulse based method developed by Burgess et al. (2001), able to accurately measure low rates of sap flow. The HRM method measures the ratio of the increase in temperature, following the release of a pulse of heat, at points equidistant downstream and upstream from a line heater. HRM configuration, correction for wounding, and other operational details are given by Burgess et al. (2001) The HRM method is sensitive to the direction of sap flow, being able to measure reverse flow in roots and other conductive organs. The HRM method is available from ICT International (see Manufacturer' Directory).

The Sapflow+ method

This method was developed by Vandegehuchte and Steppe (2012). It is a sap flux density method based on the thermodynamic theory describing heat conduction-convection in anisotropic sapwood after application of a heat pulse with finite length:

$$\Delta T = \frac{q}{4\pi\sqrt{K_{ax}K_{tg}}} \int_0^t t^{-1} \exp\left[-\frac{\rho c}{4t} \left(\frac{(x-V_h t)^2}{K_{ax}} + \frac{y^2}{K_{tg}} \right)\right] dt \quad \text{for } 0 < t < t_0$$

$$\Delta T = \frac{q}{4\pi\sqrt{K_{ax}K_{tg}}} \int_{t-t_0}^t t^{-1} \exp\left[-\frac{\rho c}{4t} \left(\frac{(x-V_h t)^2}{K_{ax}} + \frac{y^2}{K_{tg}} \right)\right] dt \quad \text{for } t_0 < t$$

where ΔT is the temperature difference (K) between the temperature at time t (s) after application of the heat pulse and the temperature before the pulse, q (W m^{-1}) is the amount of heat liberated per unit length of the heater per time, K_{ax} and K_{tg} the axial and tangential thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$), respectively, ρc the volumetric heat capacity ($\text{J m}^{-3} \text{K}^{-1}$), V_h the heat velocity (m s^{-1}) and x and y the axial and tangential distance (m) of the measurement position from the heater, respectively.

Temperature profiles are measured at distances upstream, downstream and tangentially from the heater. These measurements can be conducted at different depths to obtain a radial sap flux density profile. By fitting the theoretical heat conduction-convection equations to the measured temperature profiles, including a correction for natural temperature changes within the sapwood, heat velocity, axial and tangential thermal conductivity and volumetric heat capacity can be derived. If then once dry wood density is determined from a wood core, water content of the sapwood can be estimated throughout the measurement period. The combination of determined heat velocity and water content results in sap flux density values. The integration of a tangential measurement makes the method sensitive towards the entire naturally occurring sap flux density range.

Similar as for other heat pulse methods, wound corrections need to be applied and accurate spacing is crucial to obtain reliable results. A requisite of the method is that the heat input q is known. This heat input can be determined based on a calibration in a medium with known thermal properties such as stabilised water or can be derived from an in-situ calibration process.

The Transient Thermal Dissipation method (TTD)

This method is an empirical evolution of the thermal dissipation or heat dissipation (HD) method with constant heating and radial dual-needle probe of Granier (1985). The TTD last evolution is described in Do et al. (2011). The innovations are that 1) it uses a transient heating of 10 minutes and 2) it can be applied to a single-needle probe. Following non stationary measurements, the heating duration corresponds to the full reach of the slow asymptotic increase of temperature before equilibrium. The reference temperature baseline is given by the time-interpolation of temperatures before heating. The thermal index is based on the ratio between the maximum relative increase under zero flow and the relative increase under the measured flow. An empirical calibration has been assessed over several tree species and artificial porous media (Isarangkool Na Ayutthaya et al. 2010, Do et al. 2011). However for absolute values, specific calibration or cross-calibration are always recommended in the particular conditions of the experiment. Compared to the HD method, the TTD system has several advantages. It saves energy, reduces thermal interferences due to heat storage and passive thermal gradients (Cabibel et Do 1991; Do and Rocheteau 2002a, 2002b; Lu et al. 2004), and save money in the single-needle configuration. One limitation is the time resolution which is reduced at one measurement per 20 minutes, including 10 minutes of cooling.

TTD is a simple and robust system well adapted to large experiments requiring many probes and to environmentally-adverse conditions.

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