A unified nomenclature for sap flow measurements

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Summary A unified nomenclature for use in heat pulse measurement of sap flow is proposed. This unified nomenclature overcomes fundamental misunderstandings of the physics of heat and sap movement in wood. The nomenclature is also appropriate to other methodologies for sap flow measurement, such as heat balance methods.

Keywords: heat balance, heat pulse velocity, sap flux, sap velocity.

Introduction Over the past decade, there has been a proliferation of methods that measure sap flow within stems. There are two broad methodological categories: heat pulse methods, which use pulses of heat as markers in the sap stream, and heat balance methods, which measure the components of heat transport from a continuous heat input. There has been confusion about the terminology of the heat pulse methods, mainly because of misunderstandings about the relationship between the movements of heat and fluid in the xylem. Reports based on heat balance methods (Daum 1967, Ėermá et al. 1976, Sakuratani 1981, Granier 1987) have been more consistent because of the inherent simplicity of the underlying theory.

In this paper, we review briefly the various steps in deriving sap flow from heat pulse velocity and define each element. We detail the terms used by major authors in the field, especially in more recent publications. Finally, we suggest a unified nomenclature, compatible with the Système Internationale (SI), that will help to clarify the frequently confusing reports and avoid perpetuating these problems. This nomenclature is compatible with the heat balance methodology.

A variety of probe configurations and calculations have been devised to obtain heat pulse velocity (Marshall 1958, Swanson and Whitfield 1981). The compensation method, originally conceived by Huber and Schmidt (1937), is the most widely used. Because time is the primary measurement, the compensation method is remarkably 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. Regardless of the configuration, relating the resulting heat pulse velocity to sap velocity requires interpretation of the results within the physical framework of a porous medium, the xylem.

Heat and fluid are transported within a porous medium in a manner that is well understood (Carslaw and Jaeger 1947). Heat is transported both by conduction and by convection as mass flow. Fluid is transported by mass flow alone. Because heat can interchange with the xylem matrix, a heat pulse transported in fluid mass flow tends to be left behind in a predictable manner. The process is analogous to the transport of a dye spot in a chromatography plate, in which the spot also gets left behind according to its propensity to interact with the chromatographic medium.

We must clearly distinguish between the heat pulse velocity, which we observe, and sap velocity. Although Zimmermann and Brown (1980) are frequently cited as a comparative reference for sap velocities, the values they report are heat pulse velocities, and are therefore inappropriate. Marshall (1958) describes movement of the heat pulse within “the stationary wood and the moving sap act(ing) like a single medium...”; i.e., heat interchanges freely between sap and the wood. He pointed out that the ratio between sap velocity in the vessel or tracheid lumens and heat pulse velocity is proportional to three other ratios: (i) the ratio of conducting lumen area to total sapwood area, (ii) the ratio of sap density to density of the sap + xylem matrix, and (iii) the ratio of specific heat of sap to that of the sap + xylem matrix.

These three relationships set out the basis for a practical heat pulse estimation of sap velocity. We are normally interested in the total flow within the sapwood rather than sap velocity within the lumens, and we can find this by multiplying ratio (i) with the lumen sap velocity to give sap velocity expressed on total sapwood area. This calculation treats the entire conductive sapwood as a single medium. Note that heat pulse velocity is less than sap velocity expressed on the basis of total sapwood area, which is in turn much less than lumen sap velocity.

The practical expression of Marshall’s three ratios lies in our ability to define the density and heat capacity of the sap and sap + matrix components. This requires an assumption (or experimental measurement) of both the density and the heat capacity of the xylem matrix material. Fortunately, both parameters are remarkably constant within and among species because cell wall material is similar. Therefore, heat pulse velocity can be related to sap velocity expressed on the basis...
of total sapwood area if the volume fractions of liquid and woody matrix are known (Edwards and Warwick 1984).

There is, however, a complication: the theory of heat and fluid transport in a porous medium assumes that the medium is homogeneous. The assumption is violated when we implant probes, because the resulting wound adds a lens-shaped, nonconducting area to the tangential section. The heat pulse (and the apparent sap velocity) is slowed because there is an increase in the proportion of non-conducting tissue. This problem was addressed by Swanson and Whitfield (1981), who derived two-dimensional numerical solutions for typical probe configurations using verified computer simulations applied to heat pulse velocity. The resulting algorithms give a practical method for dealing with the problem, so that the wounding effect can be corrected for in heat pulse velocities before sap velocities are calculated.

Sap flow within the stem can be obtained as the product of sapwood area and wound-corrected sap velocity, expressed on a total sapwood area basis. Various techniques for accommodating radial and circumferential variation in sap velocity exist, and these involve integration across the sapwood radius to give sap flow.

A mixture of units has been used to express the various velocities and flows. Heat pulse velocity (cm h\(^{-1}\)) is commonly used and is probably best defined from a primary measurement. Cohen et al. (1990) used the term heat velocity and units of mm s\(^{-1}\). From heat pulse velocity, Marshall (1958) derived sap speed (cm h\(^{-1}\)) as an average value, distinguishing this from sap flux (defined by Marshall as cubic centimeters (cm\(^3\)) of sap flowing across each cm\(^2\) of sapwood perpendicular to the direction of flow in unit time). Other authors are rarely as rigorous, simply referring to sap velocity, sap flow velocity, flux per unit area, sap speed and sap flux density, variously using units of cm h\(^{-1}\), cm\(^2\) s\(^{-1}\), cm\(^3\) cm\(^{-2}\) h\(^{-1}\), 10\(^{13}\) kg m\(^{-1}\) s\(^{-1}\), or m s\(^{-1}\). Integration of sap velocity and sapwood area have variously been called xylem sap flow rate (kg h\(^{-1}\)), sap flux or sap flow (1h\(^{-1}\), kg s\(^{-1}\), mm h\(^{-1}\) or cm\(^3\) cm\(^{-2}\) h\(^{-1}\)), sap flow rate (mm\(^3\) h\(^{-1}\)), cumulative flux (l), cumulative HPV sap flow (dm\(^3\)), daily total sap flow (kg m\(^{-2}\)) and sap flow velocity (kg h\(^{-1}\)).

### A nomenclature for velocities

We propose a series of definitions using the SI nomenclature to define the velocities and flows, so that authors may adopt a consistent terminology. Suitable units for velocities are mm, cm or m per s or h. We suggest that all velocities be represented by the widely accepted italicized \(v\), and that subscripts (in roman font) be defined in terms of the above theory as shown in Table 1.

Heat pulse velocity, \(v_h\), is defined by Huber and Schmidt (1937) as:

\[
v_h = (x - x')/2t,
\]

where \(x\) and \(x'\) are the respective downstream and upstream distances of the sensors from the heater, and \(t\) is the time taken to return through the starting temperature.

Sap velocity within lumens, \(v_l\), is defined by Marshall (1958) as:

\[
v_l = \frac{v_i \rho c}{a \rho c_s},
\]

Table 1. Suggested nomenclature for velocities.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat pulse velocity</td>
<td>(v_h)</td>
<td>Huber and Schmidt (1937) (see Equation 1)</td>
</tr>
<tr>
<td>Heat pulse velocity corrected for wound effects</td>
<td>(v_c)</td>
<td>(v_h) corrected for wounding (e.g., Swanson and Whitfield 1981)</td>
</tr>
<tr>
<td>Sap velocity within lumens</td>
<td>(v_l)</td>
<td>Marshall (1958); derived from (v_c) (see Equation 2)</td>
</tr>
<tr>
<td>Sap velocity on total sapwood area basis</td>
<td>(v_s)</td>
<td>(v_l a), where (a) is the ratio of lumen area to total sapwood area</td>
</tr>
</tbody>
</table>

where \(a\) is the proportion of lumen area to total sapwood area, \(\rho\) is density, \(c\) is the heat capacity of sapwood and the subscript \(s\) refers to sap only. We have used the term \(v_h\) to replace the original \(V\) in Marshall’s (1958) equation. Marshall did not use the correction for wounding that is required for accurate estimation of sap velocity (Swanson and Whitfield 1981). Therefore, \(v_h\) should be corrected to become \(v_c\), as defined in Table 1, before Equation 2 is used to calculate \(v_l\). Note that Edwards and Warwick (1984) incorrectly applied the Swanson and Whitfield correction to \(v_l\) rather than to \(v_h\), as remarked by Olbrich (1991).

Sap velocity within lumens can be determined using markers other than heat, particularly injected dyes and isotopes. However, if the dyes or isotopes interchange with, or are adsorbed onto the xylem conduits, the resulting apparent velocity will be less than the true sap velocity within lumens, in the same way that heat pulse velocity, \(v_h\), is less than \(v_l\).

In strict physical terms, we should use speed rather than velocity to describe sap flow, because a scalar rather than a vector quantity is measured. However, the term velocity is too entrenched to be abandoned and the distinction is not critical here. The term sap flux density refers to a flow divided by the area of conducting tissue. Although use of the term has been expanded to include point measurements and even flows divided by projected crown area, we suggest that the term sap flux density not be used to report sap flows because of ambiguity in whether it is defined on a point or areal basis. It is also incorrect to use the term for heat pulse estimates of sap velocity, because they are made at a point. We recommend that all velocities be expressed in units of mm s\(^{-1}\) to comply with SI units and to facilitate comparisons among studies.
A nomenclature for sap flows

The term flux refers to “the amount of some quantity flowing across a given area (often a unit area perpendicular to the flow) per unit time” (Lapedes 1978). The integral of sapwood area and sap velocity may be referred to as sap flux or sap flow. We have chosen to use sap flow \( (Q) \).

Calculation of sap flows from point measurements of sap velocities (derived from heat pulse velocities) typically comprise either the integration of a fitted curve of velocities with depth when rotated about the axis (Edwards and Warwick 1984) or the addition of concentric rings, each characterized by a single velocity (Hatton et al. 1990). In both cases velocity (vertical) is multiplied by sapwood area (horizontal). Appropriate dimensions are \( L^3 T^{-1} \), with units of \( \text{mm}^3 \) or \( \text{m}^3 \text{s}^{-1} \) or \( \text{day}^{-1} \), depending on tree size and experimental protocol.

Sap flows from heat balance methods are frequently reported as \( \text{kg s}^{-1} \text{(M} \text{T}^{-1}) \) because of the theory behind the technique and the method of calculation. Although \( \text{kg} \) is an acceptable SI unit, we prefer conversion to dimensions of \( L^3 T^{-1} \), because these dimensions generally relate better to hydrological and other field studies, and thereby facilitate interdisciplinary comparisons. Therefore, where appropriate, we suggest that the same terms, dimensions and units that we advocate for measurements based on heat pulse methods should also be used for heat balance methods.

Because of plant size effects and the hydrological nature of many studies, it is often preferable to express sap flow on the basis of area rather than per tree; i.e., as a flow density. Table 2 presents the five commonly used lumped-parameter bases, and our suggested nomenclature for each. All except the first \( (L^3 T^{-1}) \) have dimensions of \( L^3 T^{-1} L^{-2} \), i.e., sap flow per unit area.

Regressions of sapflow \( (Q) \) on measures of tree size such as basal area or projected crown area often fail to pass through the origin. In such cases, \( Q_b \) and \( Q_c \) will not be free of size effects and should therefore be employed cautiously.

To avoid confusion with velocity measurements, and to emphasize the areal basis of the “-related” sap flow measurement (the term “-specific” should never replace the term “-related”, because, within the SI system, “specific” is exclusively reserved to describe a value per unit mass), we recommend that the dimensions of \( L^3 T^{-1} \text{L}^{-2} \) not be reduced to \( L \text{T}^{-1} \). Appropriate units for each dimension are, respectively, \( \text{m}^3 \) or \( \text{mm}^3 \), \( \text{s}^{-1} \), \( \text{h}^{-1} \) or \( \text{day}^{-1} \), and \( \text{m}^{-2} \) or \( \text{mm}^{-2} \). However, water use by a stand of trees could be expressed in \( \text{mm} \text{d}^{-1} \) if total water use by the stand is then divided by stand area. Likewise, results for individual trees might be expressed according to other criteria, such as per unit area of ground occupied.

It is our hope that the nomenclature detailed here will lead to a more coordinated approach in the literature and thereby avoid some of the problems of interpretation that have occurred in the past.

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References


Table 2. Suggested nomenclature for sap flows.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sap flow</td>
<td>( Q )</td>
<td>Sap flow per tree</td>
</tr>
<tr>
<td>Leaf-related sap flow</td>
<td>( Q_l )</td>
<td>Sap flow per unit leaf area supported by the stem above the measurement point</td>
</tr>
<tr>
<td>Crown-related sap flow</td>
<td>( Q_c )</td>
<td>Sap flow per unit projected crown area supported by the stem above the measurement point</td>
</tr>
<tr>
<td>Sapwood-related sap flow</td>
<td>( Q_s )</td>
<td>Sap flow per unit conducting sapwood area at the measurement point</td>
</tr>
<tr>
<td>Basal area-related sap flow</td>
<td>( Q_b )</td>
<td>Sap flow per unit basal area at the measurement point</td>
</tr>
</tbody>
</table>