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Evaluation of the heat pulse velocity method for measuring sap flow in *Pinus patula*

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Abstract

Information on the water use of *Pinus patula* plantations is required to predict the impact of forest plantations on water resources in South Africa. The heat pulse velocity (HPV) method is a promising technique for measuring water use by trees, and has been shown to measure sap flows accurately in a variety of hardwood trees. This method has not been sufficiently verified for pine trees where the presence of a strongly-defined ring structure in the sapwood gives rise to a complex radial pattern of sap flow. The purpose of this study was to compare water uptake by cut trees to simultaneous HPV sap flow measurements in the same tree. Fourteen trees were used for this comparison. Results showed that HPV sap flow estimates consistently overestimated cut-tree uptake by an average of 49%. The bias is attributed to heat averaging across non-conducting latewood rings. Water uptake was found to be highly correlated to the product of under-bark cross-sectional area and wound-corrected mean HPV, and it is suggested that this empirical relation provides a more appropriate way of estimating water use by this species.

Key words: Heat pulse velocity, sap flow, *Pinus patula*, transpiration.

Introduction

There is widespread concern in South Africa over the hydrological consequences of establishing pine and eucalypt plantations in areas which were previously grasslands or under agricultural crops. While some catchment data are available to infer the hydrological impact of such changes in land use (van Lill *et al.*, 1980), spatial extrapolation of results is unwise in view of the heterogeneous topography and climate within afforested areas. Consequently, process models are being developed to simulate evapotranspiration from forest and grassland canopies on the basis of local weather station data.

Pinus patula is the most important softwood timber species in South Africa, and is found on 48% of the total softwood plantation area of 611 956 ha (Crafford *et al.*, 1994). It is widely planted in the upper reaches of important mountain catchments, but little is known of transpiration rates by this species. The heat pulse velocity method of measuring sap flow in trees appears to be the most promising technique for measuring water use by *P. patula*. Advantages include minimal disturbance to the tree, relatively reliable and inexpensive technology, good time resolution of sap flow, and automatic data collection and storage. Access to the canopy is not necessary since the probes can be inserted at the base of the trunk. The method does not alter canopy boundary layer conditions, and whole-tree sap flow can be monitored in all weathers. Sequential or simultaneous measurements on numerous trees are possible, permitting the estimation of transpiration from whole stands of trees. Earlier reports of discrepancies between HPV and sap flow (Doley and Grieve, 1966; Swanson, 1974; Cohen *et al.*, 1981) were shown by Swanson and Whitfield (1981) to be due largely to sap flow interruption in the vicinity of implanted probes. Numerical solutions applicable to a variety of heat pulse sensing configurations have been undertaken by these authors, and the validity of HPV-based transpiration estimates incorporating these corrections has been established for a number of tree species (Swanson, 1983; Green and Clothier, 1988; Olbrich, 1991).

The method is most suitable for use on trees with uniform sapwood and a predictable radial HPV profile. The extent to which the presence of distinct growth rings

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in pines affects sap flow estimation is poorly understood. There is no flow in latewood rings (Harris, 1961; Booker and Kininmonth, 1978) where lumen areas are smaller and hydraulic conductivity is substantially lower than in earlywood. Latewood rings would therefore be expected to reduce the area of functional xylem in the sapwood zone of the trunk. In addition, the latewood rings would be expected to influence measurement of sap flow where temperature sensors are positioned close to a latewood/earlywood boundary (Swanson, 1983). In one of the few detailed studies performed to test HPV-based sap flow measurements of plantation pines against an independent measure of transpiration, Hatton and Vertessy (1990) found that sap flow rates exceeded Bowen ratio evaporation rates by an average of 37% over 4 d. By contrast, Cohen *et al.* (1985) showed the heat pulse technique to underestimate actual water use by Douglas fir by 47%. The purpose of the study reported here was to test the validity of HPV sap flow estimates in *Pinus patula*, and to determine whether the method can be used for the routine measurement of water use in this species.

Materials and methods

Experimental sites

Sample trees were chosen from two sites on Frankfort State Forest in the Mpumalanga province of South Africa. Six trees with relatively wide rings were chosen at an experimental site where a fast rate of growth was promoted by good soil and weed control measures, and a wide spacing of 3 × 3 m. These trees were 3-years-old. A further eight trees, mostly with narrow growth rings, were selected in an area recently clearfelled of mature *P. patula*. These self-sown trees were 3–10-years-old and had become established beneath the canopy of the mature trees. The generally narrow growth rings reflected poor growth rates resulting from severe competition with the mature trees. No heartwood was present in any of the sample trees. The field-work lasted from 21 January to 2 September 1992.

Sap flow measurement

Measurements of heat pulse velocity (HPV) were performed on each sample tree using a 'Custom' HPV recorder and sensor system (Horticulture and Food Research Institute of New Zealand, Private Bag 11030, Palmerston North, New Zealand). Eight probe sets were inserted into the trunk, and spaced at approximately equal distances around the circumference. The probe sets were also separated vertically from each other by a minimum distance of 10 cm (Swanson, 1983) to ensure that heat produced at one probe set would not interfere with heat recorded at adjacent sample positions. Six probe sets were inserted to random depths in the outer half of the trunk radius (but not closer than 0.5 cm to the cambium), while the remaining two were inserted to random depths within the inner half of the trunk radius. This sampling strategy was adopted in light of previous experience with this species (Dye *et al.*, 1991). Each probe set consisted of a line heater and two temperature measuring probes. Three vertically aligned holes were drilled radially into the sapwood at each selected sampling position, using a 1.85 mm diameter drill bit. A drilling jig with a thickness of 20 mm was used to ensure that the holes were drilled parallel to one another and at the correct vertical spacing. The heater was inserted into the central hole and the temperature-sensing probes were implanted in the upper (downstream) and lower (upstream) holes, 10 mm and 5 mm from the heater, respectively. The line heater consisted of a steel tube with an outside diameter of 1.8 mm. Temperature probes consisted of a single thermistor sealed within a Teflon tube of similar diameter. Each sensor probe thus gave a point estimate of sapwood temperature. The upper and lower thermistors were connected as opposite arms in a Wheatstone bridge configuration and the bridge was adjusted to zero output before each heat pulse. The Custom recorder was programmed to apply a current of 30 A, lasting 0.5 s, to each of the heaters in the eight probe sets. Heat pulses were initiated manually, as required.

HPV (u) was measured for each probe set using the compensation technique (Huber and Schmidt, 1937; Swanson, 1974). The temperature rise was measured at distances X_u upstream and X_d downstream from the heater, and u was calculated as follows:

$$u = (X_u + X_d)/2t \tag{1}$$

where t is the time delay for the temperatures at points X_u and X_d to become equal.

The following cut-tree procedure took place in the early morning of a subsequent cloudless or partly cloudy day. The sample tree, previously roped to a sturdy log tripod for support, was cut near ground level and the exposed end quickly immersed in a large bucket, after which a further 1–2 cm of wood was removed with a sharp chisel. The purpose of re-cutting was to remove the wood exposed to air during the cutting procedure, to ensure that uptake of water was not inhibited by air-blocked tracheids. At half-hourly intervals through the day, a further 1–2 cm of wood was chiselled away from the cut end of the trunk, to remove the wood blocked by resin exudation which followed the previous cut. The bucket was replaced by a smaller container with a diameter only slightly larger than that of the trunk. During this procedure, the cut end of the trunk was enclosed in a plastic bag to prevent exposure to air. The water level was brought up until the surface meniscus was just broken by the tip of a needle clamped in a fixed vertical position. Uptake of water by the tree was then recorded over the following 5 or 10 min, after which the water level was brought up to the datum level again with a known amount of water poured from a measuring cylinder. Uptake rates were expressed in units of litres per hour. Near the middle of each uptake period, a heat pulse was manually initiated to obtain a simultaneous reading of heat pulse velocity at each probe set.

Analysis of heat pulse velocity data

At the conclusion of each experiment, trunk segments containing the drilled holes were removed to measure precise probe separation distances at the original thermistor insertion depth. These distances were measured to the nearest 0.1 mm.

Heat pulse velocities were corrected for sapwood wounding caused during the drilling procedure. Swanson and Whitfield's (1981) wound correction coefficients were used to derive corrected heat pulse velocities (u). The correction takes the form:

$$u' = p + qu + r(u)^2 \tag{2}$$

where p, q and r are the correction coefficients appropriate to the measured wound size, diameter of Teflon probes, and probe separation distances, respectively. The size of the wound at each probe set location was measured at the end of the experiment. The eight sections of the tree trunk containing the probe implantation holes were excised. Each block was recut longitudinally at the particular depth below the cambium where the thermistor was originally positioned. The exposed, fresh face was shaved smooth using a microtome, after which the wound width was clearly identified by its lighter colour. The widths at positions midway between the heater and each thermistor probes were measured to the nearest 0.1 mm using a 7× scale lens.

The corrected heat pulse velocities were converted to sap flux density (v) using the following equation (Marshall, 1958):

$$v = \rho_b/\rho_s\,(m_c + c_{dw}/cs)u' \quad (3)$$

where ρ_b = dry wood density (g cm^{-3}), ρ_s = density of sap (g cm^{-3}), assumed equal to water, m_c = moisture fraction of sapwood, c_{dw} = specific heat of dry wood (J g^{-1} K^{-1}), assumed constant at 0.33 (Dunlap, 1912), and c_s = specific heat of sap (J g^{-1} K^{-1}), assumed equal to water. Wood density was calculated as dry weight/volume of a freshly excised section of wood. Volume was determined in the field by immersing the fresh wood sample in water and applying Archimedes' principle. Moisture fraction was calculated as (fresh weight–dry weight)/dry weight.

Total sap flow was calculated by summing the product of mean sap flux density and cross-sectional area for both the inner and outer sample areas. The area of dysfunctional xylem caused by drilling was taken into consideration in calculating sap flow.

Results and discussion

A summary of parameters relevant to the calculation and evaluation of sap flow data is given in Table 1.

The relation between cut-tree uptake and HPV sap flow estimate for all 14 trees is shown in Fig. 1. Comparison of the fitted linear regression to a 1 : 1 line shows that the heat pulse estimates of sap flow consistently overestimate measured uptake from the water container. A probable cause of this bias, which averages 49%, is the presence of latewood rings in the sapwood. It has been shown in several pine species that sap flow does not take place in latewood rings (Harris, 1961; Booker and Kininmonth, 1978; Whitehead and Jarvis, 1981). Dye uptake experiments by Booker and Kininmonth suggest that a typical sap velocity profile would approximate to the shaded area bounded by line A in Fig. 2. It has also been demonstrated (Dye *et al.*, 1991) from radial heat pulse velocity profiles in *P. patula* trees that non-zero values of HPV are recorded even when the probes are situated in the centre of a latewood ring (line B in Fig. 2). This is attributed to heat being conducted into the latewood ring tissue from adjacent earlywood rings. Clearly sap flow will be overestimated for areas within and immediately adjacent to latewood rings. Some underestimation may also be possible in earlywood rings as a result of heat loss to latewood rings. Swanson (1983)

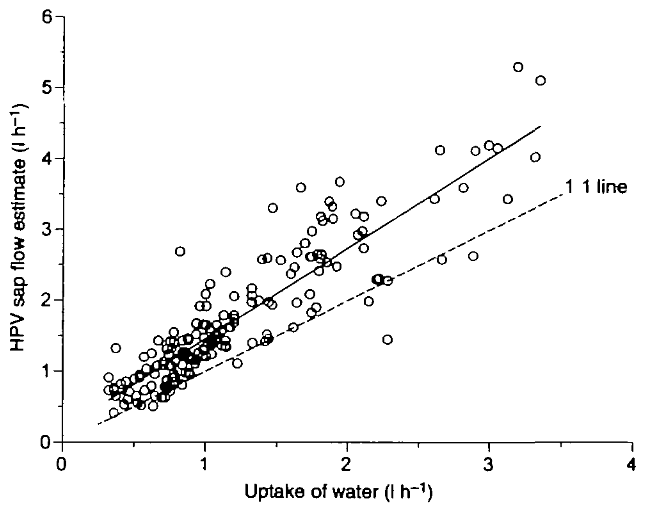

Fig. 1. The relation between cut-tree water uptake rates over 5–10 min periods and simultaneous estimates of sap flow based on heat pulse velocity measurements on 14 sample trees of *Pinus patula*.

Table 1. *A summary of parameters used in the calculation and evaluation of sap flow in sample trees*

Maximum wound-corrected HPV (u') is the highest recorded at any time during the course of the day by any one of the eight probe sets. Minimum wound-corrected HPV is the lowest reading of the remaining seven probe sets recorded at the same time as the maximum reading.

Tree no.	Under-bark diameter (cm)	Mean wound width (cm)	Maximum u' (cm h^{-1})	Minimum u' (cm h^{-1})	Wood density (g cm^{-3})	Moisture fraction	Diameter/no. of rings
1	11.8	0.294	81.9	18.71	0.343	2.002	1.97
2	6.5	0.284	81.74	42.09	0.32	2.216	1.63
3	10.8	0.369	136.68	44 22	0.347	1.994	2 7
4	12.5	0.238	55.61	12.16	0.421	1.429	2 08
5	7.8	0.261	82.73	18.4	0.344	1.922	1.95
6	6.5	0.308	492.25	53.93	0.314	2.457	1.08
7	10.1	0.281	84.33	28.02	0.426	1.566	0.84
8	6.5	0.259	64.08	23.18	0.339	1.925	0.54
9	6.4	0.293	58.14	25.57	0.398	1.756	0.53
10	8.4	0.295	130.74	53.34	0.43	1.502	0.7
11	7.3	0.335	53.59	21.12	0.415	1.498	0.61
12	9.4	0.318	53.37	19.06	0.398	1.608	0.78
13	13	0.333	96.63	24.02	0.493	1.073	0.65
14	14.3	0.25	45.08	16.13	0.368	1.489	1.02

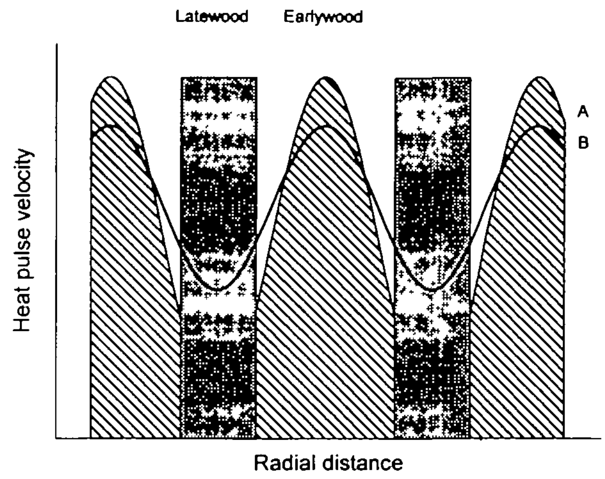

Fig. 2. Diagram of a longitudinal section of pine sapwood comparing hypothesized true sap flux density (bounded by line A) and sap flux density estimated from HPV (line B).

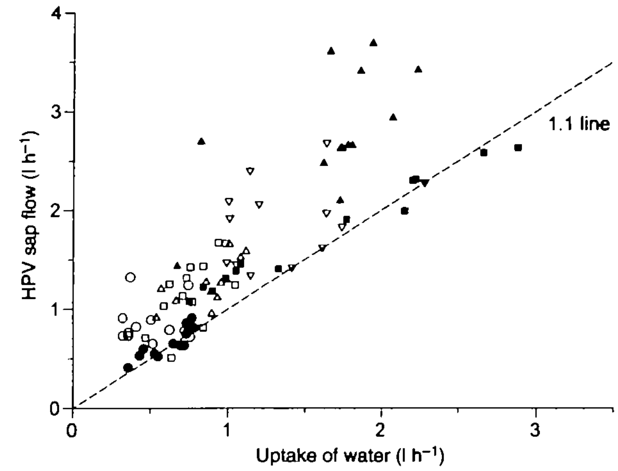

Fig. 4. The relation between cut-tree water uptake and simultaneous HPV sap flow estimates for the following seven sample trees: tree 8 (○); tree 9 (●); tree 10 (□); tree 11 (■); tree 12 (△); tree 13 (▲); tree 14 (▽).

showed through measurement and simulation that HPV measured within 1.0 cm of a zero flow boundary will be underestimated on the side with flow, and overestimated on the no-flow side. The degree of bias is therefore likely to be affected by the relative widths of the latewood and earlywood rings.

A large scatter in data points was recorded for certain trees, as shown in Figs 3 and 4. Since measurement of water uptake is thought to have been very accurate, the scatter is believed to be largely due to spatial changes in permeability of the exposed wood following each new cut. Such changes, by altering sap flow rates passing each probe set, would increase the variability of HPV sap flow estimates. A comparison of heat pulse times recorded before and after cutting by the same four sets of probes supports this hypothesis. A high degree of correlation exists between the probes in the intact tree (Fig. 5),

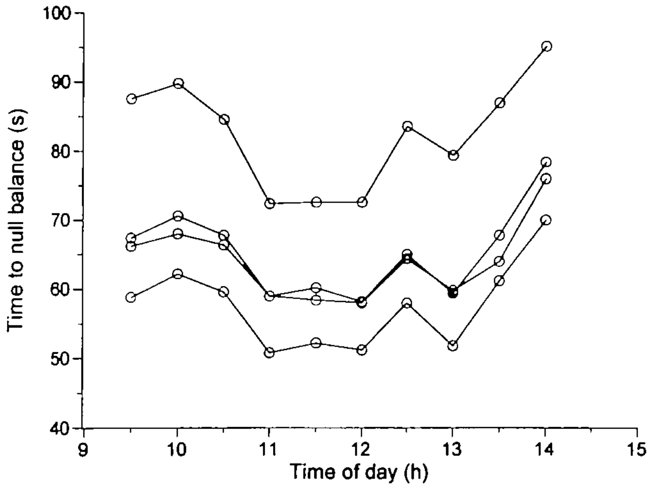

Fig. 5. Times to null balance recorded at 30 min intervals by probes inserted at four depths in the sapwood of an uncut tree.

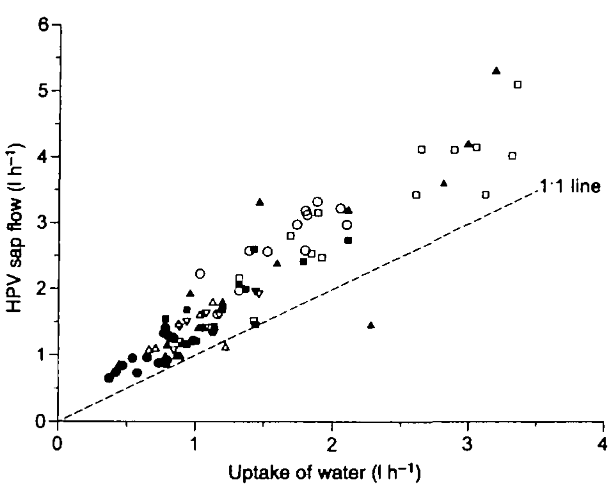

Fig. 3. The relation between cut-tree water uptake rates and simultaneous HPV sap flow estimates for the following seven sample trees: tree 1 (○); tree 2 (●); tree 3 (□); tree 4 (■); tree 5 (△); tree 6 (▲); tree 7 (▽).

whereas poor correlation is evident between the probes on the day of the cut-tree procedure (Fig. 6), when the end of the stem was recut before every measurement. It is probable, therefore, that scatter in the relationship between true sap flow and HPV sap flow estimates would be substantially less in an intact tree. The trends in the relationships are therefore of more significance in evaluating the usefulness of the HPV method.

Linear regressions were performed on the data from each sample tree, to examine these trends. Fitted lines for all 14 sample trees are shown in Fig. 7. Trees not conforming to the general trend are numbered. The slopes of 10 of these fitted regression lines are very similar, but four show a degree of convergence towards the 1 : 1 line as water uptake increases. One cause is believed to be an insufficient range of data points to describe the slope

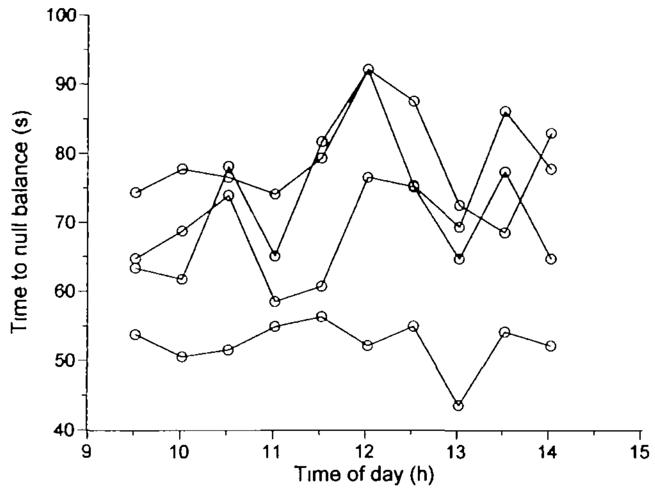

Fig. 6. Times to null balance recorded at 30 min intervals by the same probes yielding data shown in Fig. 5. A fresh cut preceded each measurement time.

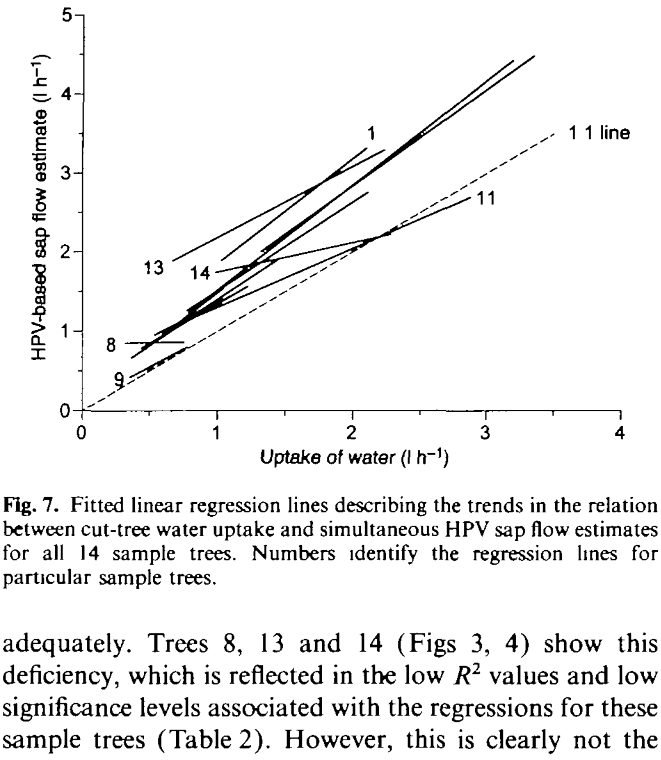

Fig. 7. Fitted linear regression lines describing the trends in the relation between cut-tree water uptake and simultaneous HPV sap flow estimates for all 14 sample trees. Numbers identify the regression lines for particular sample trees.

adequately. Trees 8, 13 and 14 (Figs 3, 4) show this deficiency, which is reflected in the low R^2 values and low significance levels associated with the regressions for these sample trees (Table 2). However, this is clearly not the case with tree number 11, suggesting a probable additional cause.

Figure 7 also shows that some variation exists between the trees in the degree of departure from the 1 : 1 line. A possible explanation is that variation in ring widths causes varying degrees of overestimation among the trees. Between-tree differences in the proportion of latewood are expected to be reflected in the wood density measurements in Table 1, while mean ring width is reflected by the quotient of stem diameter and number of latewood rings across the diameter. It is evident from Table 1 and Fig. 7 that neither of these two parameters is obviously

Table 2. *Statistics describing linear regressions fitted to data showing the relation between measured uptake of water and HPV-based sap flow estimates*

Tree no.	Slope	Intercept	R^2	F	Obs
1	1.332±0.261	0.522±0.436	0.722	25.98	12
2	1.154±0.265	0.238±0.191	0.633	18.99	13
3	1.224±0.18	0.392±0.448	0.808	46.34	13
4	1.126±0.261	0.384±0.35	0.65	18.59	12
5	1.001±0.292	0.345±0.274	0.495	11.78	14
6	1.330±0.261	0.191±0.511	0.722	25.92	12
7	1.129±0.207	0.272±0.229	0.748	29.75	12
8	0.017±0.342	0.849±0.187	0	0	13
9	0.897±0.155	0.102±0.1	0.752	33.4	13
10	1.332±0.495	0.155±0.386	0.397	7.25	13
11	0.742±0.035	0.560±0.062	0.976	439.6	13
12	0.880±0.279	0.479±0.25	0.498	9.924	12
13	0.902±0.333	1.284±0.573	0.4	7.324	13
14	0.370±0.303	1.379±0.432	0.119	1.49	13

correlated with the degree of departure from the 1 : 1 line shown by the various trees. The differences among the trees in the degree of overestimation are believed to be due largely to chance differences in the proportions of earlywood and latewood sampled by the thermistor probes implanted to randomly-assigned depths.

It is concluded that the analysis of HPV data using theory based on the assumption of a homogeneous sapwood leads to overestimates of sap flow in *P. patula*. Corrections based on ring dimensions, proportion of latewood, or the proximity of thermistors to different rings are unlikely to be practical for routine measurement of water use in trees. Consequently, the question as to whether an empirical relationship between mean HPV, cross-sectional area and sap flow could be used to predict water use by trees was explored. The relation between the product of mean HPV (uncorrected for wound width) and cross-sectional area, and water uptake by the cut trees is shown in Fig. 8. The correlation is evidently poor, especially under conditions of relatively high sap flow. However, correlation is considerably improved when wound-corrected HPV is used (Fig. 9), demonstrating that significant differences in wound widths occurred between the various probe sets and sample trees (Table 1). A cause of variation in wound widths was found to be spirality of wood grain. In the absence of spirality, all three drilled holes essentially disrupt the same tracheids, so that wound width is minimal. Where spirality exists, however, each hole disrupts a group of different, adjacent tracheids, leading to wider than expected wound widths.

The linear regression equation predicting sap flow from wound-corrected HPV and under-bark cross-sectional area is shown in Fig. 9. It is significant that very little additional variation is accounted for in converting corrected HPV to sap flux densities (Fig. 9, $R^2 = 0.790$; Fig. 1, $R^2 = 0.803$). This is attributed to the reciprocal relation between wood density and moisture fraction in the experimental trees (Fig. 10). Thus the product of dry wood

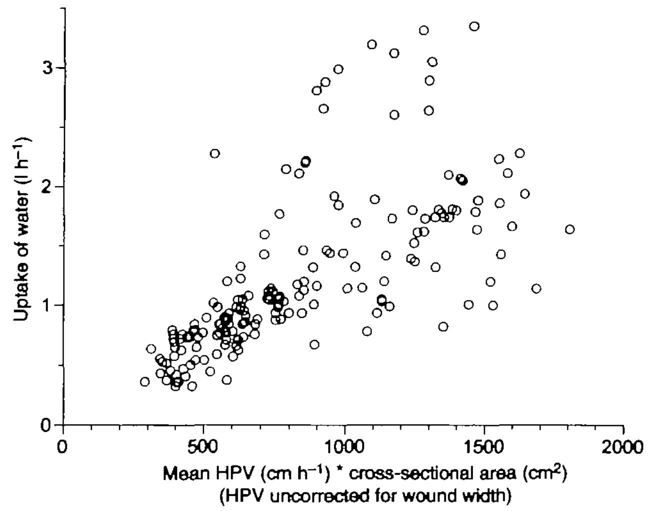

Fig. 8. The relation between cut-tree water uptake rates and the product of stem cross-sectional area (cm^2) and mean HPV (cm h^{-1}, not corrected for wound width) measured at the same times, for all 14 sample trees.

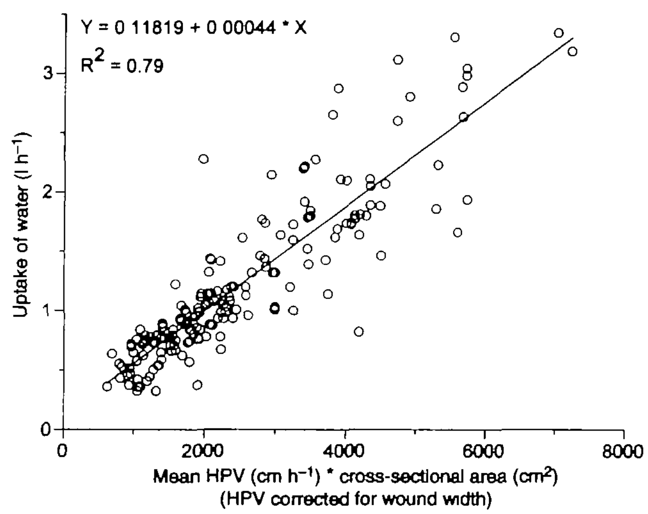

Fig. 9. The relation between cut-tree water uptake rates and the product of stem cross-sectional area (cm^2) and mean HPV (cm h^{-1}, corrected for wound width) measured at the same times, for all 14 sample trees.

density and moisture fraction plus the constant specific heat term in equation 3 is relatively constant.

The use of an empirical relationship between sap flow and the product of under-bark cross-sectional area and wound-corrected HPV is concluded to be a more appropriate way of estimating sap flow in *P. patula* trees. The approach is practical for the routine measurement of sap flows in sample trees, requiring only the measurement of HPV, probe separation distances, wound widths, and under-bark cross-sectional area. Caution should be exercised in using the relation in Fig. 9 to estimate sap flow in trees subject to significant soil water deficits, where the wood moisture fraction may decline below what is normal for unstressed trees.

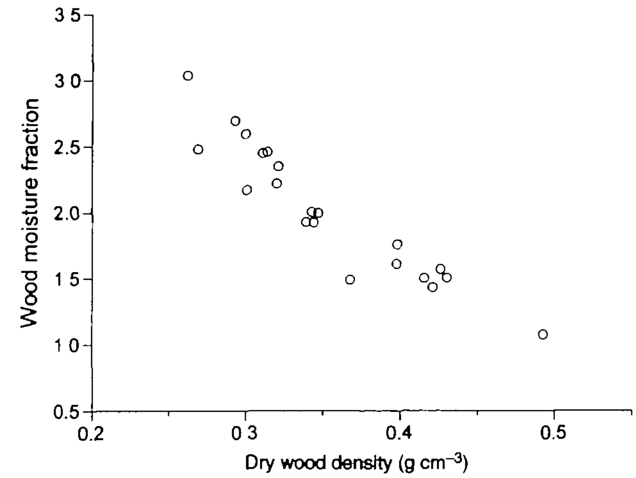

Fig. 10. The relation between dry wood density and wood moisture fraction.

It is not possible to define the accuracy with which the equation in Fig. 9 will predict sap flow, since it has been shown that much of the variation in this relation is probably a consequence of the cutting treatment. However, the uniformity of trends displayed by the linear regression lines in Fig. 7, as well as relatively high correlation evident in Fig. 9 suggest that the HPV method will provide acceptable estimates of transpiration rates, especially when based on sap flow measurements taken in several sample trees, and integrated over the longer time periods of interest in hydrological studies.

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