

Heat dissipation sensors of variable length for the measurement of sap flow in trees with deep sapwood

SHELLEY A. JAMES,¹ MICHAEL J. CLEARWATER,² FREDERICK C. MEINZER^{3,4} and GUILLERMO GOLDSTEIN¹

¹ Department of Botany, University of Hawaii, 3190 Maile Way, Honolulu, HI 96822, USA

² HortResearch, Te Puke Research Centre, 412 No. 1 Road RD2, Te Puke, New Zealand

³ USDA Forest Service, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331, USA

⁴ Author to whom correspondence should be addressed (fmeinzer@fs.fed.us)

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Summary Robust thermal dissipation sensors of variable length (3 to 30 cm) were developed to overcome limitations to the measurement of radial profiles of sap flow in large-diameter tropical trees with deep sapwood. The effective measuring length of the custom-made sensors was reduced to 1 cm at the tip of a thermally nonconducting shaft, thereby minimizing the influence of nonuniform sap flux density profiles across the sapwood. Sap flow was measured at different depths and circumferential positions in the trunks of four trees at the Parque Natural Metropolitano canopy crane site, Panama City, Republic of Panama. Sap flow was detected to a depth of 24 cm in the trunks of a 1-m-diameter *Anacardium excelsum* (Bertero & Balb. ex Kunth) Skeels tree and a 0.65-m-diameter *Ficus insipida* Willd. tree, and to depths of 7 cm in a 0.34-m-diameter *Cordia alliodora* (Ruiz & Pav.) Cham. trunk, and 17 cm in a 0.47-m-diameter *Schefflera morototoni* (Aubl.) Maguire, Steyerm. & Frodin trunk. Sap flux density was maximal in the outermost 4 cm of sapwood and declined with increasing sapwood depth. Considerable variation in sap flux density profiles was observed both within and among the trees. In *S. morototoni*, radial variation in sap flux density was associated with radial variation in wood properties, particularly vessel lumen area and distribution. High variability in radial and circumferential sap flux density resulted in large errors when measurements of sap flow at a single depth, or a single radial profile, were used to estimate whole-plant water use. Diurnal water use ranged from 750 kg H₂O day⁻¹ for *A. excelsum* to 37 kg H₂O day⁻¹ for *C. alliodora*.

Keywords: *Anacardium excelsum*, conducting xylem, *Cordia alliodora*, *Ficus insipida*, radial profile, sap flux density, scaling, *Schefflera morototoni*, tree water use.

Introduction

Transpiration by branches and whole trees is most easily estimated by measuring sap flow. Among the methods for determining sap flow (Smith and Allen 1996), the most common

and feasible techniques for use with large-diameter trees are the heat pulse method and the thermal dissipation method developed by Granier (1985). Scaling water use to the whole-tree or stand-level based on either sap flow method is limited by the accuracy with which the sapwood or functional xylem area, and the radial variation in sap flux density can be determined (Meinzer et al. 2001). Sap flow in trees is typically measured over a relatively narrow range of sapwood depths close to the vascular cambium where sap flow is often maximal (Jiménez et al. 2000, Lu et al. 2000). For trees with deep sapwood, fluctuations or decreases in sap flow with increasing depth in the sapwood result in large errors in estimates of whole-tree mass flow extrapolated from measures over a restricted range near the vascular cambium.

To date, heat pulse and thermal dissipation sensors have been limited to a maximum depth of 14 cm (e.g., Miller et al. 1980, Cohen et al. 1981, Dye et al. 1991, Hatton et al. 1995, Phillips et al. 1996, Jiménez et al. 2000, Lu et al. 2000, Pausch et al. 2000). Such a length does not always adequately encompass the range of sapwood depths found in large trees. Gradients in sap flux density along the length of the thermal dissipation sensor measuring element can result in large errors in estimated sap flow (Clearwater et al. 1999), especially when using probes with long measuring elements. The advantages of thermal dissipation sensors over heat-pulse systems are that the alignment of the probes is not as critical, the sensors are inexpensive and easy to manufacture and use, and are readily interfaced with data loggers for remote operation. However, unlike the heat pulse system, constant heat sap flow sensors do not give a direct measure of sap velocity because values are based on an empirical calibration that predicts sap flux density.

Lu et al. (2000) developed 20-cm-long, Granier-style constant heat sensors that had 2-cm-long effective measuring elements, but the probes were described as being too fragile to move frequently, especially when placed deep in the trunk. The aim of this paper is to describe a new design of heat dissipation sensor that is robust, has a short effective measuring el-

ement or tip (1 cm), and can be inserted into the sapwood over a wide range of depths. The consequences of using different sapwood area criteria to scale from measures of sap flux density at different sapwood depths to sap flow and whole-tree water use were also assessed.

Materials and methods

Probe construction

The sensor design was modeled after that of Granier (1985, 1987), but the effective measuring element was reduced to a length of 1 cm and the maximum depth of measurement was not fixed. Each sensor consisted of two probes, a continuously heated downstream probe, and an unheated upstream probe. The probes were constructed of polyetherketone (PEEK) tubing (0.76-mm inside diameter, 1.6-mm outside diameter) ranging from 3 to 30 cm in length, with a 1.2 cm aluminum tip (2.3-mm-diameter tubing, 0.35 mm thick) crimped to the final 2 mm of the PEEK tubing (Figure 1). Aluminum tips of both probes contained a junction of a copper-constantan differential thermocouple (PFA-teflon coated wires, 0.12-mm diameter; Omega Engineering, Stanford, CT). The constantan wire connecting the two probes was placed within fluorinated ethylene propylene (FEP) tubing (0.8-mm inner diameter; Cole Parmer, Vernon Hills, IL) for protection, and the copper wires were soldered to two lead wires (0.32-mm² two-pair shielded cable; Belden Wire and Cable, Richmond, IN). A 9-mm-long heater coil consisting of about 25 cm of insulated nichrome wire (RediOhm-675, 436 Ω m⁻¹; H.P. Reid, Palm Coast, FL) with a final resistance of about 100 Ω was placed within the heated probe tip. The two ends of the coil were soldered to insulated copper magnet wire (0.01 mm²). The magnet wire ran the length of the PEEK tubing and was soldered to the remaining two lead wires. Each thermocouple junction was projected and secured 5 mm outside the PEEK tubing with cyanoacrylate glue. All soldered junctions were covered with liquid insulation or heat-shrink tubing, and the crimped aluminum tip was filled with a polyester resin or slow-setting epoxy resin.

At the base of the PEEK tubing, the lead wires and the FEP tubing were secured within a disposable automatic pipette tip filled with polyester or epoxy resin. Any probes found to have electrical contact between the aluminum tubing, thermocouple or heater wires were discarded.

Power supply

Heated probes were powered by a constant current supply set to provide 0.15 W per probe. The entire system was powered by a 12-V transformer connected to mains power, and the current was adjusted to 0.039 A with an adjustable voltage regulator and variable 100- Ω potentiometer.

Data collection

The sensors were tested on four trees, *Anacardium excelsum* (Bertero & Balb. ex Kunth) Skeels (Anacardiaceae), *Cordia alliodora* (Ruiz & Pav.) Cham. (Boraginaceae), *Ficus insipida* Willd. (Moraceae) and *Schefflera morototoni* (Aubl.) Maguire, Steyer. & Frodin (Araliaceae) in Parque Natural Metropolitano, Panama City, Republic of Panama (09°10' N, 79°51' E, elevation 50 m), at the site of the Smithsonian Tropical Research Institute canopy crane. Two replicate sets of sensors were inserted into opposite sides of the trunk of each tree at a height of 1.5 m for a 26-m-tall *C. alliodora* tree and a 22-m-tall *S. morototoni* tree, at 3.1 m for a 38-m-tall *A. excelsum* tree, and above the buttress roots at 3.5 m for a 28-m-tall *F. insipida* tree. Sensors were inserted at five depths in the trunks of *A. excelsum*, *F. insipida* and *S. morototoni*, and at four depths in the smaller *C. alliodora* (Table 1). The canopy crane was used to install two sets of three sensors in the trunk of *C. alliodora* below the first major branch (16.3 m height) in circumferential positions corresponding to the sensors lower in the trunk. The upper and lower trunk series were expected to give similar values of sap flux density and estimates of whole-plant water use. Two 38-gauge (2.58 mm) holes per sensor, separated vertically by 10 cm, were drilled into the trunk to a maximum depth of 30 cm (the length of the drill bit). The sensors were placed in an upward spiral around the tree, 5-cm apart vertically and circumferentially at successive depths.

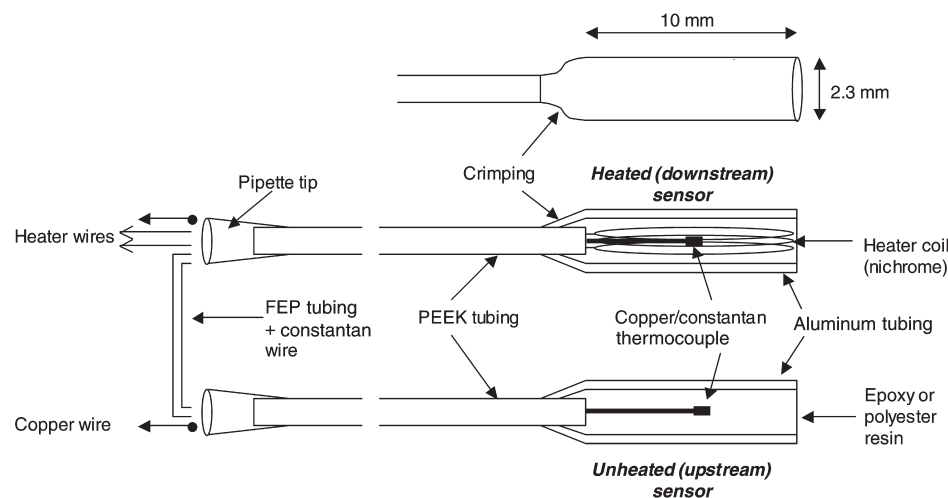


Figure 1. Details of the heated and unheated probes of a variable length heat dissipation sensor illustrating the positions of thermocouple and heater wires, and crimping of the 1.2-cm aluminum tip to the final 2 mm of variable length PEEK tubing (not to scale).

Table 1. Stem diameter at sensor insertion, estimated depth to heartwood (HW) and the depth of the sap flow sensors beneath the cambium within the lower (L) and upper (U) trunk of *Cordia alliodora* and the lower trunk of *Schefflera morototoni*, *Anacardium excelsum* and *Ficus insipida*.

Species	Diameter (cm)	HW depth (cm)	Sensor depth in sapwood (cm)				
			1	2	3	4	5
<i>Cordia alliodora</i> - L	34	11	1.7	4.0	7.0	11.0	–
<i>Cordia alliodora</i> - U	20	7	1.7	4.0	7.0	–	–
<i>Schefflera morototoni</i>	47	20	1.3	3.6	7.6	13.6	17.9
<i>Anacardium excelsum</i>	98	35	1.5	4.0	10.0	17.0	24.0
<i>Ficus insipida</i>	65	30	1.5	4.0	10.0	17.0	24.0

The tips of the probes were coated with thermally conductive silicone heat sink compound before insertion.

Special precautions were sometimes required to avoid irreversible bending damage to the PEEK tubing shaft during insertion of the deepest probes. In these cases, the PEEK tubing was gripped with forceps or needle-nose pliers a few mm from the outer surface of the sapwood and inserted gradually. The sensors were protected from direct sunlight and rainfall by reflective insulation. Differential voltage measurements across the copper thermocouple leads were converted to a temperature difference between the heated and reference probe (ΔT). Signals from sap flow sensors were measured every minute and 10-min means were recorded by a data logger (CR10x or CR21x; Campbell Scientific, Logan, UT) equipped with a 32-channel multiplexer (AM416; Campbell Scientific) and stored in a solid-state module (SM192; Campbell Scientific).

Data analysis

Data were collected from January to April 2000 for *C. alliodora* and *S. morototoni*, and from February to March 2001 for *A. excelsum* and *F. insipida*, during the Panamanian dry season. Photosynthetic photon flux density (PPFD) and air temperature were monitored continuously with a quantum sensor (Li-Cor, Lincoln, NE) and a temperature probe (HMP35C, Campbell Scientific) by an automated weather station installed on the canopy tower in the upper canopy (about 25 m height). The temperature difference between the two probes (ΔT) was converted to sap flux density (v ; $\text{g m}^{-2} \text{s}^{-1}$) using the calibration of Granier (1985), recently revalidated by Clearwater et al. (1999), and validated for the new sensor design as:

$$v = 119k^{1.231}, \quad (1)$$

where $k = (\Delta T_m - \Delta T)/\Delta T$ and ΔT_m is the temperature difference when sap flux density is zero. The rate of sap flow for each sensor (F ; g s^{-1}) was calculated as:

$$F = vA. \quad (2)$$

The cross-sectional area of the sapwood (A ; m^2) measured by each sensor was calculated as either (1) the ring area consisting of the sapwood between the outer surface of the sapwood and the first probe tip, and between sequential probe

tips, up to and including the measurement probe tip (to sensor tip); or (2) the ring area centering on the measurement probe tip and extending to midway between two successive probe tips (between sensors). The innermost sensor was considered to measure the sap flux density for the sapwood area to the center of the trunk, or to the beginning of the heartwood. Sapwood area was calculated based on the assumption of radial symmetry. Sap flow measurements for each replicate set of sensors were scaled to a whole-tree basis using the two criteria for calculating sapwood area for each sensor. For comparison, whole-tree water use was also estimated by assuming a uniform radial profile of sap flux density based on sap flow values for the two outermost sensors (to 4-cm depth).

Anatomical confirmation

On completion of the sap flow measurements, wood cores of up to 30 cm in length were collected with a 5-mm-diameter increment borer at the position in the trunk corresponding to the sap flow sensors. Samples were stored in water at 5 °C until they could be placed in fixative (10% formaldehyde, pH 8.0). Segments of 10-mm length, subdivided into two 5-mm samples, were taken from the corresponding position of each sensor measuring tip. Sections of 55- μm thickness were cut with a freezing cryotome (Cryocut 1800, Reichert-Jung, Leica Microsystems, Wetzlar, Germany) and mounted in frozen tissue embedding medium (HistoPrep, Fisher Scientific, Fairlawn, NJ). Sections were photographed at 25 $\times$ magnification in three regions, and the images (six per sensor) were digitized. Vessel sizes were determined using SigmaScan Pro 4 (SPSS, Chicago, IL). After calibrating the images, the perimeters of the vessels were outlined, and the lumen area computed. The cross-sectional area occupied by vessel lumens as a proportion of the image (wood) area was calculated and averaged for each sensor position. Only the anatomical results for *S. morototoni* are presented.

Results

The diurnal time course of sap flux density reflected diurnal changes in ambient temperature and PPFD (Figure 2). Sap flux density increased shortly after sunrise, reached a peak by 1000 h and decreased in the late afternoon. The magnitude of sap flux density of the four trees varied according to the depth of the sensor in the sapwood (Figures 2 and 3). Of the four

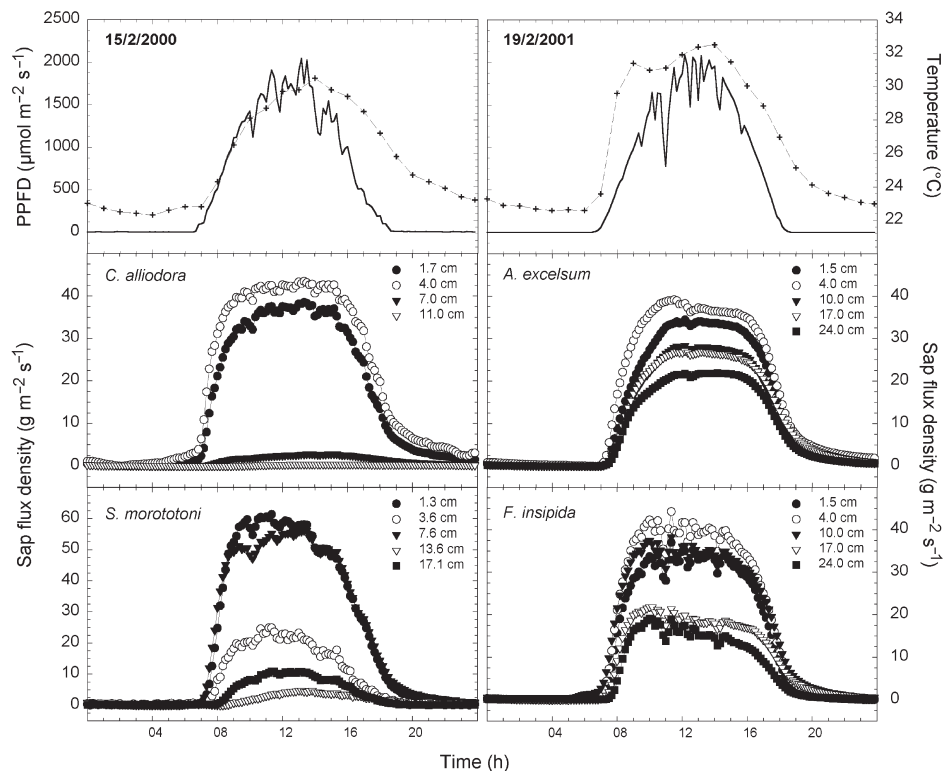


Figure 2. Representative diurnal courses of photosynthetic photon flux density (PPFD; —), ambient temperature (—+—) and sap flux density with sapwood depth in the lower trunks of *Cordia alliodora*, *Anacardium excelsum*, *Schefflera morototoni* and *Ficus insipida* during the dry season at Parque Natural Metropolitano canopy crane site, Panama. Only one replicate series of sensors is shown for each tree.

trees, *S. morototoni* had the highest maximum sap flux densities ($63 \text{ g m}^{-2} \text{s}^{-1}$). *Cordia alliodora* had the shallowest sapwood ($\leq 7 \text{ cm}$), followed by *S. morototoni* (20 cm) (Figure 3). *Ficus insipida* and *A. excelsum* had substantial sap flux densities ($> 15 \text{ g m}^{-2} \text{s}^{-1}$) at a depth of 24 cm (Figure 3). Heartwood depth, as determined by the sensors, was consistent with visual assessment of wood cores for *C. alliodora* and *S. morototoni*, but was subjectively estimated to be 35 cm for *A. excel-*

sum and 30 cm for *F. insipida* for the calculations of whole-tree water use (Table 1).

Although sap flux density generally diminished from the outermost to the innermost sensor, it was highly variable with sapwood depth in all four trees (Figures 2 and 3). In *C. alliodora*, sap flux density decreased sharply from its maximum value at about 2 cm to near zero at 7 cm, whereas in *S. morototoni*, sap flux density initially fluctuated with increasing sap-

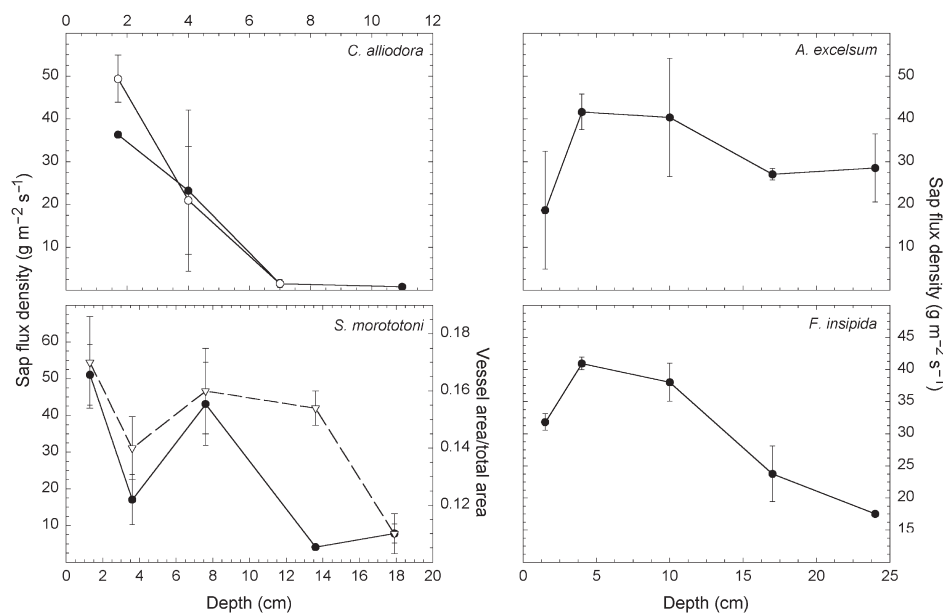


Figure 3. Mean sap flux density in relation to sapwood depth near the base (●) of four trees (*Cordia alliodora*, *Anacardium excelsum*, *Schefflera morototoni* and *Ficus insipida*) and in the upper trunk (○) of *Cordia alliodora* at Parque Natural Metropolitano canopy crane site, Panama on a representative day in February 2000 or 2001. Values are the means from 1000 to 1400 h of two replicate sensors at each sapwood depth. The vessel lumen area to total wood area at the positions of the five sensors within the *Schefflera morototoni* trunk (▽) is also shown.

wood depth before declining to near zero at about 13.5-cm depth. By contrast, sap flux density of *A. excelsum* and *F. insipida* initially increased to a sapwood depth of 4 cm, then declined gradually (*F. insipida*), or remained relatively constant with increasing depth (*A. excelsum*). The sap flux density profiles for *C. alliodora* at comparable positions in both the upper and lower trunk were consistent (Figure 3). For *S. morototoni*, the variability in sap flux density with sensor depth was partly associated with radial variation in wood characteristics. Vessel lumen area per unit wood area of *S. morototoni* showed radial fluctuations similar to those of sap flux density (Figure 3). Although a high ratio of vessel area per sapwood area was found at a depth of about 14 cm, the sap flux density at this depth was low, indicating a high proportion of nonfunctional vessels.

Scaling to whole-tree water use was sometimes strongly influenced by the method of estimating the sapwood area characterized by each sensor (Table 2). For example, dividing the sapwood of *C. alliodora* and *S. morototoni* into rings centered on each probe tip produced estimates of whole-tree water use that were 23 to 40% greater than those obtained when the sapwood rings were delimited by sequential probe tips. For *A. excelsum* and *F. insipida*, however, estimates of whole-tree water use based on the two sapwood area criteria typically differed by less than 10%. Circumferential variation in radial profiles of sap flow had an even greater impact on estimates of whole-tree water use than differences in criteria used to define the sapwood area for a given sensor (Table 2). Whole-tree water use calculated from replicate series of sensors differed by as much as 100%. These large differences were mostly attributable to variability in sap flux density in the outermost sapwood layers, which constituted the largest fraction of the total sapwood area (Figures 3 and 4). Even in a small stem, such as that of *C. alliodora*, the position of the sensors influenced the value of sap flux density obtained and the extrapolation to whole-tree water use.

The exclusion of heartwood in whole-tree water use calculations substantially changed the values only for *A. excelsum*, where the heartwood area accounted for 7% of the total wood cross-sectional area compared with 0.2% for *F. insipida* (Table 2). With the exception of *A. excelsum*, low sap flux densities and small sapwood area of the inner sapwood and heartwood reduced the differences in heartwood and non-heartwood estimates. Scaling of sap flow based solely on sap flux densities of the outer layers of sapwood (first and second probe depths) also greatly over- or underestimated diurnal water use, depending on the positions of the sensors around the trunk (Figure 4).

Discussion

The variable-length heat dissipation (sap flow) sensor design described here is inexpensive to construct and is compatible with readily available data loggers. Reduction in the length of the measuring tip of the probe from the widely used 2 cm, to 1 cm, meant that estimation of sap flux density at the different sapwood depths was less susceptible to errors associated with abrupt changes in water conducting and sap flow properties between adjacent layers of sapwood. The ability to place the sensor at multiple depths is also beneficial for determining sapwood depth and area, particularly when sapwood cannot be distinguished from heartwood by color or xylem water content.

Improved accuracy in the measurement of sapwood depth and spatial variability in sap flux density are possible with the outlined sensor design, and as a consequence, whole-tree sap flow and water use can be determined if spatial replication of measurements is adequate. Lu et al. (2000) gave equations for the estimation of whole-tree water use, extrapolating from sap flow in the outer 2 cm of sapwood, based on an exponential decline in sap flux density with increasing depth. However, the species included in the present study showed highly variable

Table 2. Diurnal water use determined by extrapolating from the sap flow of each series of sensors (A and B) within the four trees, assuming the presence or absence of heartwood (HW), and with different criteria for estimating the sapwood area corresponding to each sensor (see text). Data represent means and standard errors for 54–56 days from February to April 2000 for *Cordia alliodora* and *Schefflera morototoni*; and 22 days for *Anacardium excelsum* and 55 days for *Ficus insipida* from February to March 2001 at Parque Natural Metropolitano canopy crane site, Panama.

Species	Position	Diurnal water use (kg day ⁻¹)			
		Sapwood area to sensor tip		Sapwood area between sensors	
		HW	No HW	HW	No HW
<i>Cordia alliodora</i>	Lower - A	27 ± 0.4	28 ± 0.4	29 ± 0.4	30 ± 0.4
	Lower - B	48 ± 0.9	49 ± 0.9	62 ± 1.2	62 ± 1.2
	Upper - A	23 ± 0.5	23 ± 0.5	30 ± 0.6	30 ± 0.6
	Upper - B	19 ± 0.4	19 ± 0.4	27 ± 0.5	28 ± 0.5
<i>Schefflera morototoni</i>	Lower - A	65 ± 2	65 ± 2	80 ± 2	81 ± 2
	Lower - B	110 ± 3	111 ± 3	136 ± 3	136 ± 3
<i>Anacardium excelsum</i>	Lower - A	887 ± 19	954 ± 20	879 ± 19	946 ± 20
	Lower - B	590 ± 15	626 ± 15	621 ± 13	657 ± 13
<i>Ficus insipida</i>	Lower - A	349 ± 9	349 ± 9	371 ± 9	372 ± 9
	Lower - B	284 ± 8	284 ± 8	313 ± 8	314 ± 8

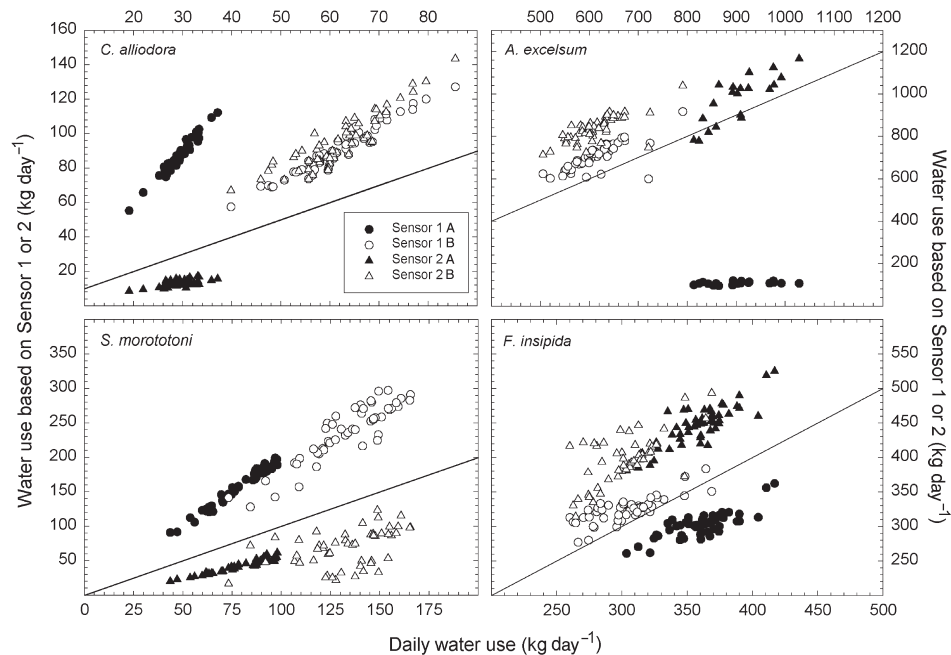


Figure 4. Diurnal water use of *Cordia alliodora*, *Anacardium excelsum*, *Schefflera morototoni* and *Ficus insipida* during 2 to 3 months of the 2000 or 2001 dry season calculated based on values of sap flow measured by sensors installed across the entire radial profile (sapwood area corresponding to each sensor extending to the point midway between successive sensors) (x-axis), or extrapolated using only sap flow measured by the two outermost sensors (Sensor 1 and 2; y-axis). Values for the two replicate series of sensors (A and B) are shown separately. The lines indicate a 1:1 relationship.

radial profiles of sap flux density, preventing extrapolation to whole-tree water use from sap flow measurements over such a restricted sapwood depth. Because the total area of the outer sapwood is substantially greater than that of the inner sapwood, circumferential variation in sap flux density in the outer sapwood has a pronounced effect on the estimation of whole-tree water use (Jiménez et al. 2000).

The two criteria used in the estimation of sapwood area per sensor resulted in different values of sap flow and diurnal water use, largely because of a difference in the estimates of outermost sapwood area where sap flux density was highest. Sap flow in the innermost annuli of sapwood of the four Panamanian trees studied contributed relatively little to estimates of total sap flow because of their small cross-sectional area and low values of sap flux density. Similar results have been reported by Dye et al. (1991) and Lu et al. (2000). Sap flux density has often been reported to vary throughout the sapwood, peaking 1 to 2 cm from the cambium and declining toward the heartwood (Edwards and Booker 1984, Dye et al. 1991, Hatton et al. 1995, Zang et al. 1996, Lu et al. 2000). Sap flow peaked in the outer part of the xylem of all four trees, but remained relatively constant over the whole xylem cross-sectional area in *A. excelsum*. Similar variability in radial patterns of sap flow has also been found in laurel forest tree species (Jiménez et al. 2000).

Because of circumferential variability in sap flux density (Miller et al. 1980, Lu et al. 2000, Oliveras and Llorens 2001), adequate replication around the tree trunk is required for accurate estimates of whole-tree water use. In the present study, the two replicate series of sap flow sensors in each tree yielded substantially different estimates of whole-tree water use, even for the smaller diameter *C. alliodora*. Sap flux density is affected by the individual properties of each trunk, including

sapwood conductivity, annual ring size, relative water content and sapwood specific gravity, all of which may differ circumferentially and with sapwood depth (Cohen et al. 1981, Edwards and Booker 1984, Phillips et al. 1996, Zang et al. 1996). In our study, crown exposure (Miller et al. 1980, Jiménez et al. 2000) and xylem structure would both have influenced the sap flux density profiles with sapwood depth. It is, therefore, essential that replicates with multiple sensors circle the tree in a sufficient number of locations to achieve a representative sap flux density profile, and that several replicate trees be measured if stand transpiration is required. We note, however, that the use of many closely spaced probes may seriously alter flow patterns through the sapwood, particularly in smaller trunks.

Goldstein et al. (1998) estimated that the same *A. excelsum* tree at Parque Natural Metropolitano, Panama had a water use of 379 kg day^{-1} based on measurement of sap flux density in the outermost 2 cm of sapwood. The present study, with probes of different lengths extending across the majority of the radial profile, produced an estimate of 750 kg day^{-1} . Estimates of whole-plant water use obtained by extrapolating from the 1.5-cm-deep sensors yielded a mean value of 415 kg day^{-1} , which is within 10% of the previous estimate by Goldstein et al. (1998). However, the 1.5-cm-deep sensors substantially underestimated water use of this tree because sap flux density was greater at intermediate depths than in the outermost 2 cm of sapwood. In large trees with deep sapwood, positioning of sap flow sensors at multiple points and depths around the circumference of the trunk is, therefore, critical for accurate estimates of sap flux density and for scaling to whole-tree water use. Use of the sensor design outlined here facilitates such measurements at low cost.

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