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Original article

Evaluation of Granier's sap flux sensor in young mango trees

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Abstract – Granier's technique of measuring sap flux density using a continuous heating system was tested on young mango trees. On containerized trees, sap flow underestimated transpiration measured gravimetrically by less than 10 %. In a 4-year-old field-grown tree, there was only a 5 % difference between cumulative summed sap flow in the branches and sap flow in the trunk over a 24-h period. Positioning of the sap flux sensor on the trunk was found to be non-critical for sap flow measurement in trees of diameter of less than 10 cm. Granier's sap flux sensor was sensitive to both slow and abrupt changes in canopy transpiration induced by successive branch girdling, defoliation and excision. A comparison of sap flow in the branches and water uptake by the tree measured using the 'cut-tree method' showed that sap flow method underestimated the actual water uptake by less than 6 %. The results of this study indicate that Granier's sap flux sensor is suitable for measuring whole-tree transpiration in young mango trees. (© Inra/Elsevier, Paris.)

sap flow / transpiration / leaf gas exchange / girdling / *Mangifera indica*

Résumé – Évaluation sur le jeune manguier de la méthode de Granier pour la mesure du flux de sève. La méthode de Granier a été testée sur de jeunes manguiers. Sur des arbres cultivés dans des containers, la perte d'eau par transpiration mesurée avec le fluxmètre de sève est en étroite corrélation avec celle mesurée par la méthode gravimétrique. Sur un arbre de 4 ans, une différence de seulement 5 % a été observée entre le flux de sève des branches et celui du tronc sur une période de 24 h. L'appareil de Granier a montré une bonne sensibilité aux changements lents ou brutaux de la transpiration de l'arbre provoqués successivement par incision annulaire, défoliation et excision de branches sur le même arbre. Une comparaison entre le flux de sève et l'absorption d'eau par l'arbre mesurée avec la méthode de l'arbre coupé, a montré que la méthode du flux de sève sous-estimait légèrement (< 6 %) la quantité d'eau absorbée. Les résultats de cette étude montrent que la méthode de Granier est fiable pour la mesure de la transpiration sur les jeunes manguiers. (© Inra/Elsevier, Paris.)

flux de sève / transpiration / échanges gazeux / incision annulaire / *Mangifera indica*

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1. INTRODUCTION

To induce reliable flowering and to obtain high yield in mango (*Mangifera indica* L.) in the seasonally wet–dry tropics, a pre-flowering dry period of 2–3 months and, subsequently, irrigation from peak flowering to fruit maturity are considered necessary [5, 16]. Therefore, to develop optimal orchard management practices, a precise knowledge of the water requirement of mango trees and its relationship to productivity is essential. As part of a study on mango flowering behavior and productivity in northern Australia, we are currently investigating whole-tree transpiration during the wet and dry seasons by measuring xylem sap flow.

During the past two decades, several thermoelectric sap flow measuring systems have been developed that allow direct measurement of sap flow in trunk or branch, e.g. the heat balance gauge [18], the stem tissue heat balance system using steel-plate electrodes [4], the heat-pulse method [6, 13] and Granier's continuous heating system [8, 9]. The heat balance gauge is preferred for trees of small diameter (< 15 cm [17]) while the stem tissue heat balance system is designed for trees of large diameter. The heat-pulse method has been successfully applied to a large range of tree species. However, because the heat-pulse method is based on 'point' measurement of sap flow velocity [12], it appears that it is difficult to measure sap flow in trees with substantial spatial variability in sapwood, such as kiwifruit vines [11]. Although being without apparent heartwood, the sapwood of mango is quite heterogeneous [14]. Our previous sap flow measurement on mango using the heat-pulse sensors (Greenspan Tech., Australia) showed that sap flow velocity readings would change abruptly when the probe was moved 1–2 mm, which raised the problem of where to position the probe in mango (Lu and Wicks, unpublished). In this case, a large number of heat-pulse sensors may need to be used to cover such variability in sap flow in mango. Granier's sap flow sensor was, therefore, selected for sap flow measurement in young mango trees, as it is believed to be able to integrate the sap flow along its 2-cm long probe [9, 10] thus reducing error due to heterogeneity of sap flow over a small scale of 1–2 mm.

To evaluate the accuracy and sensitivity of Granier's method in young mango trees, sap flow was compared with actual transpirational water loss measured gravimetrically in container-grown, 2-year-old trees, and with the water uptake in a field-grown, 4-year-old tree by the 'cut-tree method' [15].

2. MATERIALS AND METHODS

Studies were carried out between September 1994 and January 1995 at Tropical Ecosystem Research Centre, CSIRO (Darwin, Australia, 12°25'S, 130°52'E). The experimental trees were of the cultivar Kensington grafted on to Kensington seedlings.

2.1. Sap flow measurements

Sap flow measurements were made with Granier's sap flux sensors [8, 9] which consisted of two, 2-cm-long probes (2.0 mm in diameter) inserted radially into the stem, one above the other 15–20 cm apart. Each probe contained a heater and a thermocouple. The upper one was heated at constant power while the lower one, which is not powered, measures the ambient temperature of the stem. The temperature difference between the two probes was influenced by the sap flux density in the vicinity of the heated probe. Sap flux density (Fd, kg dm^{-2} h^{-1}) was calculated using a relation which was calibrated on several tree species [1, 8, 9]:

$$Fd = 428.4 * [(\Delta Tm - \Delta T)/\Delta T]^{1.231} \quad (kg\ dm^{-2}\ h^{-1})$$

where ΔTm and ΔT are the temperature differences between the two probes, at zero flow and positive flow (Fd > 0) conditions, respectively.

The signal from the sap flux sensor was measured every 10 s and the average was recorded every 30 min (except on day of year – DOY– 358 during the 'cut-tree test' in which the average was recorded every 5 min) by a datalogger (Campbell 21X, Campbell Scientific Inc., USA). Total sap flow F (kg h^{-1}) was calculated as the product of sap flux density (Fd) and sapwood area at the heated probe level. Sapwood area was directly determined at the end of the experiments.

2.2. Comparison between sap flow and gravimetric measurement

Two 2-year-old container-grown mango trees were used for the comparison of transpiration determined gravimetrically with sap flow as measured by Granier's sap flow system. Tree I (diameter = 23 mm, height = 1.71 m, sapwood area = 3.8 cm^2 and leaf area = 1.36 m^2) was grown in an 18-L polyethylene bag and tree II (diameter = 31 mm, height = 1.74 m, sapwood area = 5.5 cm^2 and leaf area = 4.41 m^2) in a 55-L metal bin. Both the trees were subjected to several cycles of wet–dry soil conditions. The containers were enclosed in large polybags to prevent entry of rainwater and evaporation from the growing medium. For the gravimetric measurement, transpiration from the trees was determined by weight loss using an electric balance (maximum capacity 200 kg with the accuracy of 0.02 kg). For the sap flow measurements, one sap flow sensor was installed in the trunk of the tree at a height of about 30 cm from the base. The sensor and the trunk were thermally insulated with 2-cm-thick fibreglass extending 20 cm above the heated probe and to the base of the stem. To protect from the rain and minimize heating of the growing medium by exposure to the sun, the whole trunk (including the sensor) and the containers were then wrapped with several layers of aluminium foil.

2.3. Comparison of sap flow in the trunk and branches of a 4-year-old tree and validation of sap flow results with 'cut-tree' method

Comparison of sap flow in the trunk and branches and the evaluation of the effect of girdling, defoliation and excision of different branches on sap flow were carried out on a 4-year-old field-grown mango tree with three primary branches. Sap flux density was simultaneously measured in the main trunk on two opposite sides (east and west, 50 cm above the ground) and in three branches (B1, B2 and B3) from 25 October to 24 December 1994. The positions of the branches and sensors on the tree are shown in *figure 1*. The tree was watered each night to field capacity of the soil.

To evaluate the effect of branch girdling on sap flow in mango, a branch (B1) was girdled 15 cm above the heated sap flow probe on 10 November (DOY 314) at 1530 hours. To examine the sensitivity of the sap flow sensors to abrupt changes in transpiration, another branch (B2) was defoliated on 7 December (DOY 341),

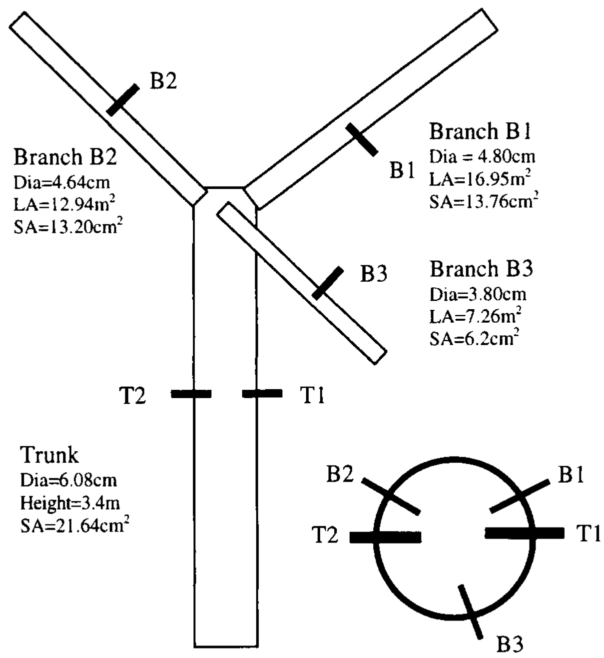

Figure 1. Sketch indicating the position of the sensors in the trunk (at T1 and at T2) and that of branches (B1, B2 and B3) of the 4-year-old field-grown mango tree (Dia: diameter; LA: leaf area; SA: sapwood area).

and further the remaining intact branch (B3) was cut off 10 cm above the heated probe on 13 December (DOY 347). Effects of the above canopy manipulations on photosynthesis, stomatal conductance and transpiration of leaves were also examined. Six leaves per branch were measured between 0800 and 1000 hours with a portable photosynthesis measuring system (LI-6200, LI-COR, USA).

For the 'cut-tree' experiment, the tree subjected to the above branch manipulations was watered to field capacity of the soil on the day before cutting. On 23 December (DOY 357) commencing at 0800 hours, the tree canopy was sprayed thoroughly with water to reduce canopy transpiration and xylem water tension and to minimize the chance of xylem embolism during the cutting. Supports were set up to maintain the tree in an erect position. At 0830 hours, the trunk was cut under water 10 cm above ground level. The cut surface was then trimmed under water with a sharp knife and quickly placed in a 4-L transparent plastic container filled with a solution containing 0.6 % filtered basic blue. The container and the base of the trunk (up to 10 cm above the container rim) were wrapped with plastic film and aluminium foil. Water uptake by the tree was regularly determined by refilling the dye solution to a predefined level. At 0830 hours the next day (24 h after the tree cutting), the girdled branch (B1) and defoliated branch (B2) were excised above the point of probe installation. Sap flow and water uptake measurements were continued during the following 5 h.

A transverse section of the trunk at about 6 cm above T1 and T2 probes was collected at the end of the experiment. Stained section was photographed and image-analysed (Image-Pro Plus software, Media Cybernetics, USA) to quantify spatial variation in staining intensity which reflects the variation in sap flux density across the trunk.

3. RESULTS

3.1. Comparison of sap flow and gravimetric measurements

The diurnal courses of sap flow and the gravimetric water loss in tree I are showed in *figure 2a*. Sap flow increased rapidly after 0800 hours to peak at about 1000 hours at a value of 0.15 kg h^{-1}. Thereafter a slow decline until 1600 hours was followed by a more rapid decline. The gravimetric water loss followed a similar pattern except that the values were in general slightly higher. Due to the relatively low accuracy of the balance, it was not possible to compare the two measurements more critically. Nevertheless, over an entire day the

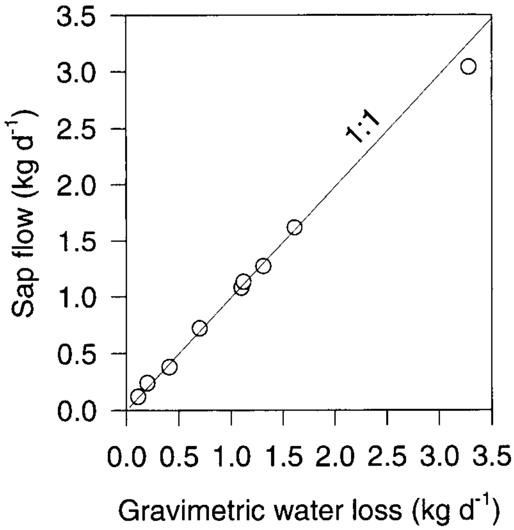

Figure 3. Comparison of daily sap flow and gravimetric water loss of the container-grown trees I and II. The 1:1 line is shown. The slope of sap flow versus gravimetric water loss, forced through the origin, was 0.95.

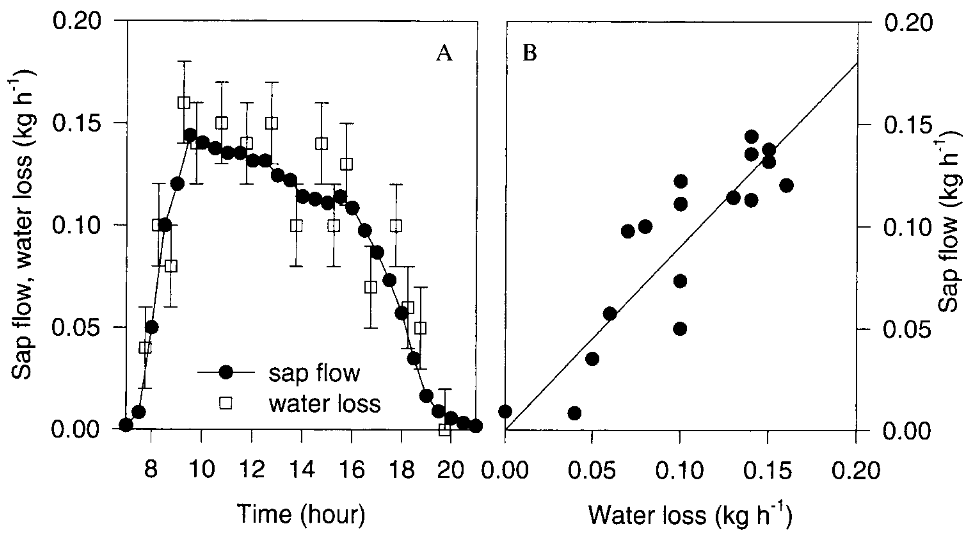

Figure 2. Comparison of sap flow and gravimetric water loss of the container-grown tree I. a) Diurnal courses of sap flow and gravimetric water loss. Error bars indicate the accuracy of the balance (0.02 kg); b) comparison of the hourly sap flow and gravimetric water

hourly sap flow was well correlated with the gravimetric water loss (sap flow = 0.90 water loss, r^2 = 0.76, n = 17, *figure 2b*). Daily sap flow and gravimetric water loss measurements in trees I and II over soil drying–wetting cycles showed good agreement (*figure 3*). The daily sap flow slightly underestimated the gravimetric water loss (sap flow = 0.95 water loss, r^2 = 0.99, n = 9).

3.2. Trunk and branch sap flow in a 4-year-old field-grown tree

At the beginning of the experiment, maximum sap flux densities in trunk and branches were similar, ranging between 3.8 and 5.0 kg dm^{-2} h^{-1} (*figure 4a*). Sap flows measured on the east (T1) and west (T2) sides of the trunk were nearly identical, and were about three times that in the branches (*figure 4b*). There was only a 5 % difference between cumulative summed sap flow in the branches (ΣF_B) and averaged sap flow in the trunk (F_T, the averaged sap flow at T1 and T2) over a 24-h period (*figure 4c*).

3.2.1. Effect of branch girdling and defoliation

Girdling B1 on DOY 314 induced a progressive decline in sap flow in B1 (*figure 5a*). In contrast, sap flow in the other two branches (B2 and B3) increased, especially in B3. The measurements of the leaf gas exchange on the tree showed a rapid decrease in net leaf photosynthetic rate (Pn), stomatal conductance (gs) and transpiration rate (E) in the branch B1 after the girdling (*figure 6*) while the leaf gas exchange remained unchanged and even increased in the other two branches.

In the trunk, sap flow at T1, a position close to B1, decreased synchronously with that in B1 (*figure 5a*); while at T2, on the side opposite B1, sap flow declined at first then eventually increased slightly. Sap flow at T1 dropped to about 60 % of that at T2 8 days after girdling (DOY 322). In the first week following girdling, a difference of 15 % was observed between the averaged sap flow in the

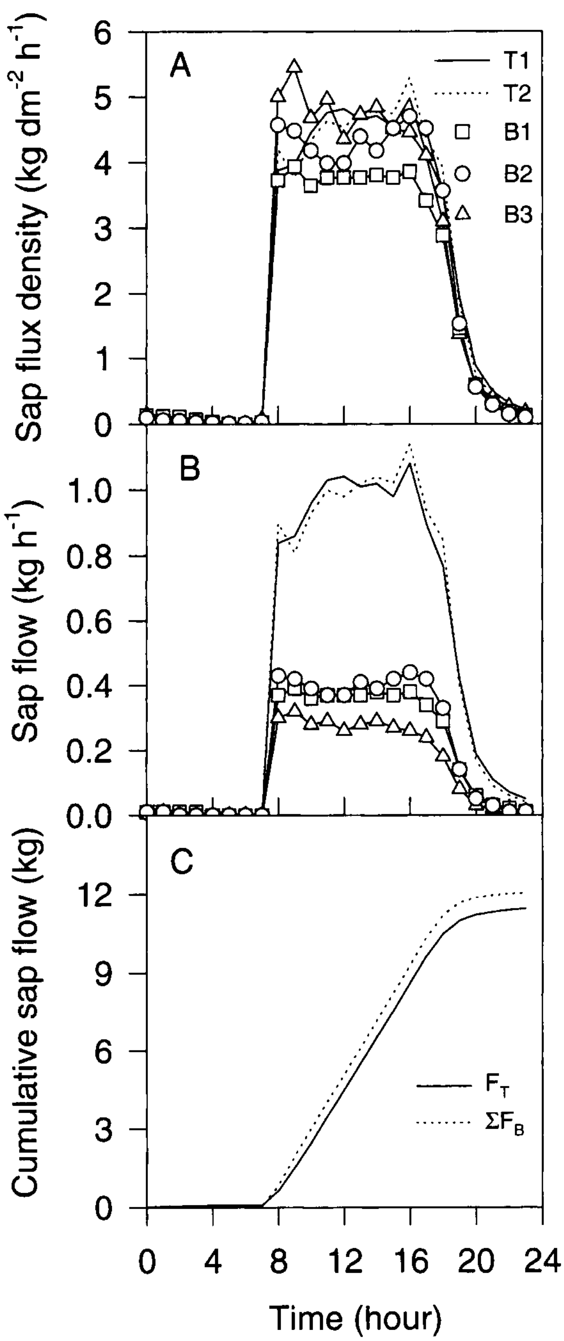

Figure 4. Sap flow measurements on the 4-year-old tree. a) Diurnal courses of sap flux density in the trunk (at T1 and at T2) and in the branches (B1, B2 and B3); b) diurnal courses of sap flow in the trunk and in the branches; c) comparison of cumulative summed sap flow in the branches (ΣF_B) and cumulative averaged sap flow in the trunk (F_T).

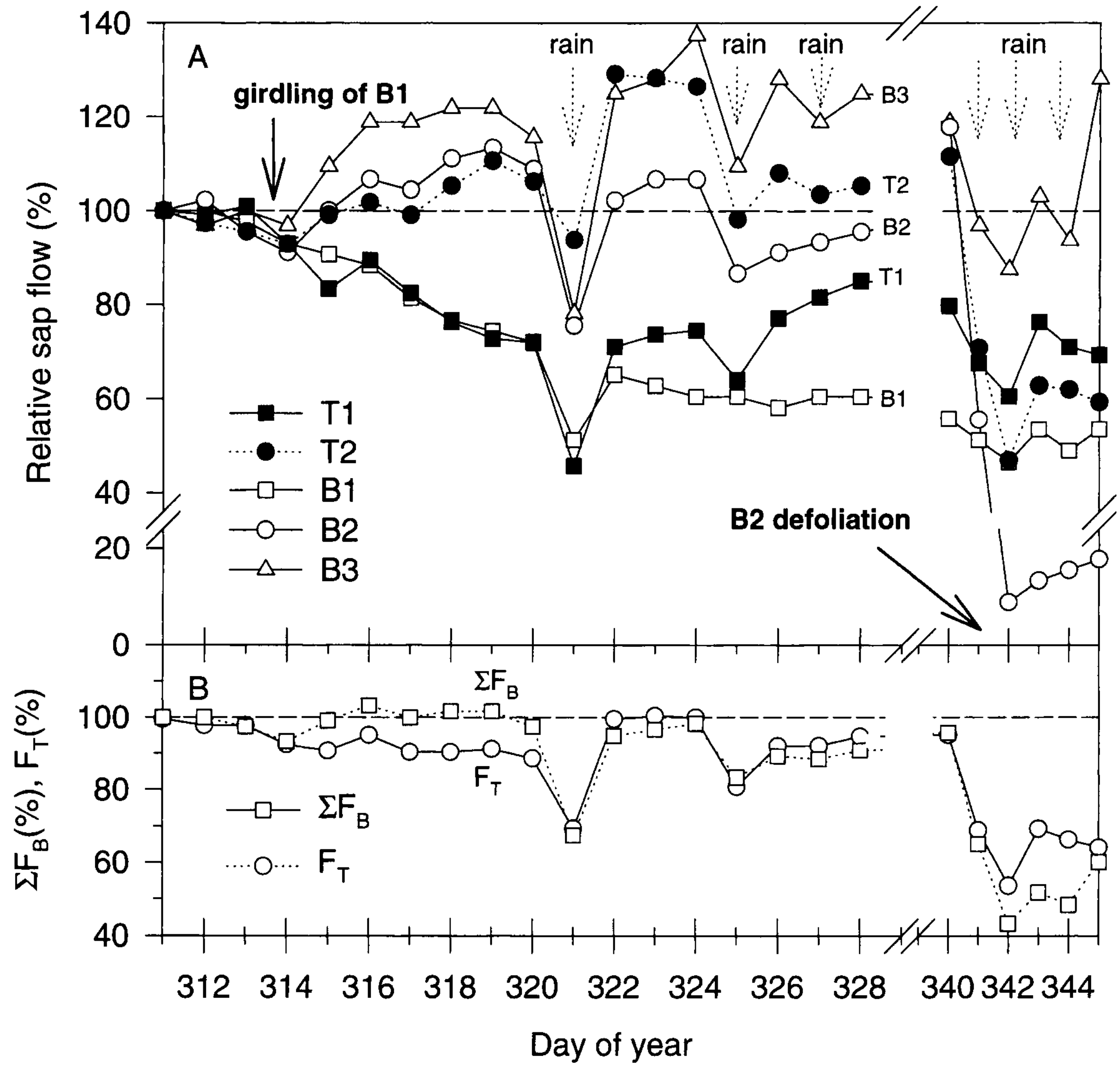

Figure 5. Daily sap flow in the trunk and in the branches of the 4-year-old, field-grown mango tree during November–December 1994. Results are expressed as percentage of the values of the DOY 311. a) Relative sap flow in the branches (B1, B2 and B3) and in the trunk (at T1 and at T2); b) summed sap flow in the branches (ΣF_B) and the average of the sap flow in the trunk (F_T).

trunk (F_T) and the sum of sap flow in the branches (ΣF_B) (*figure 5b*). This difference fell to almost zero during the second week. F_T decreased about 5–10 % (*figure 5b*), whereas ΣF_B seemed not to be affected by the girdling of B1 (except on the day of girdling, *figure 5b*) until, for unknown reasons, a decrease in B2 occurred beginning at DOY 325 (*figure 5a*). The cumulative sap flows F_T and ΣF_B over an 18-day period were very similar, showing a difference of only 7 %.

The diurnal changes in sap flow in the trunk and branches and weather conditions on the day of defoliation of another branch (B2) are presented in *figure 7*. Defoliation of B2 resulted in immediate and simultaneous declines in sap flow in B2 and at T2 (*figure 7b*); while at T1, opposite to B2, sap flow was not immediately affected. Rain occurred about 2 h after the defoliation of B2, caused a rapid decline in sap flow in all parts of the tree. After the rain, sap flow at T1 almost fully recovered to the

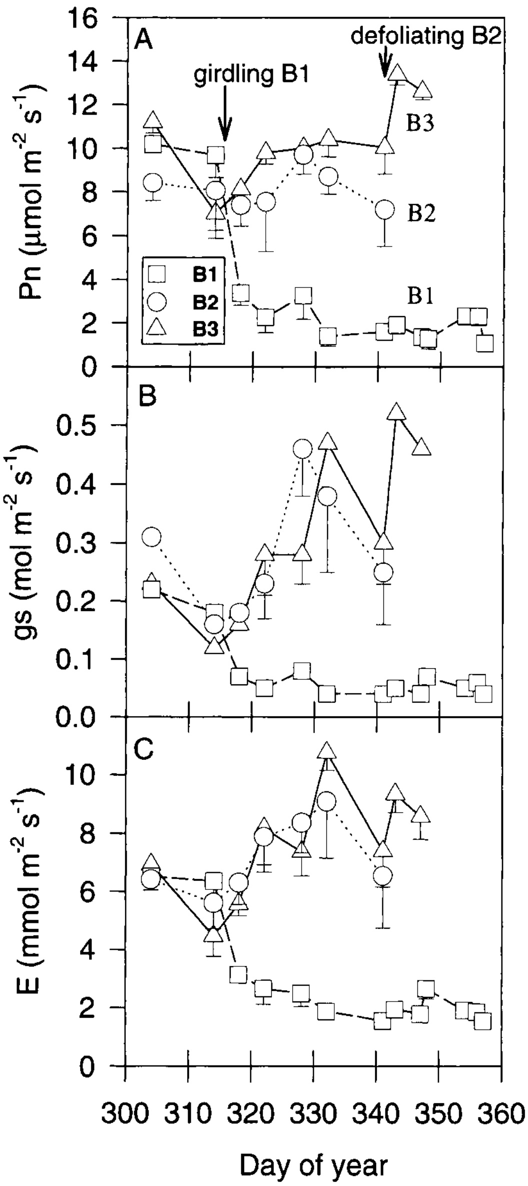

Figure 6. Effects of girdling of the branch B1 on leaf gas exchange of branches of the 4-year-old field-grown tree: a) net leaf photosynthetic rate, Pn; b) stomatal conductance, gs; c) transpiration rate, E.

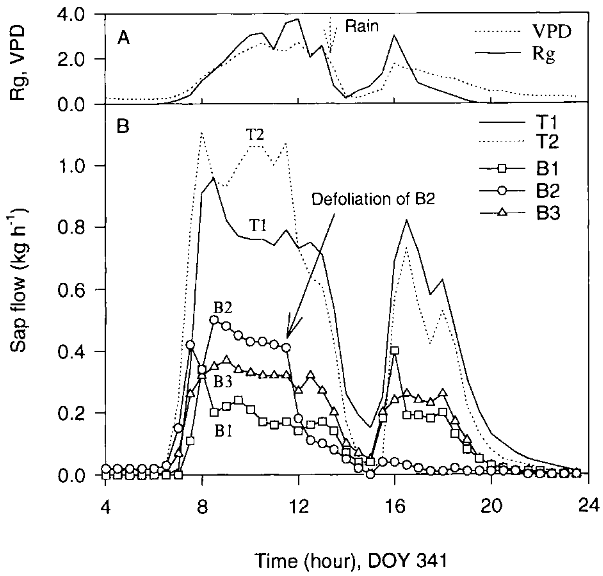

Figure 7. Responses of sap flow in branches and in trunk to branch defoliation on DOY 341. a) Diurnal courses of global radiation (Rg, MJ m^{-2} h^{-1}) and vapor pressure deficit (VPD, kPa); b) diurnal courses of sap flow in response to the defoliation of branch B2.

pre-rain level while the sap flow at T2 was significantly lower than its pre-rain level. It is also evident that daily sap flow at T2 (*figure 5a*) was more adversely affected by the defoliation of B2 than sap flow at T1 in spite of the influence of the rainy weather.

3.2.2. Effect of branch excision (figure 8)

After B3 was excised at 0930 hours on DOY 347 sap flow in the remaining branch stump declined to zero within 30 min (note: reading at 0930 hours represented the average of the readings between 0915 and 0945 hours). The effects of B3 excision on the sap flow at T1 and T2, although confounded by an afternoon of rain on DOY 347, became more obvious the next day; sap flow was more affected at T2 than at T1 (comparison between DOY 346 and DOY 348).

3.2.3. Cut-tree experiment (figure 9)

The cumulative sap flow and water uptake by the tree over 24 h following the trunk excision is presented in *figure 9*. F_T is the average of the sap flow on both sides of the trunk, and ΣF_B is the sum of the flow in the girdled branch B1 and the defoliated branch B2 (with limited sap flow due to water loss from leafless young twigs). The amount of water

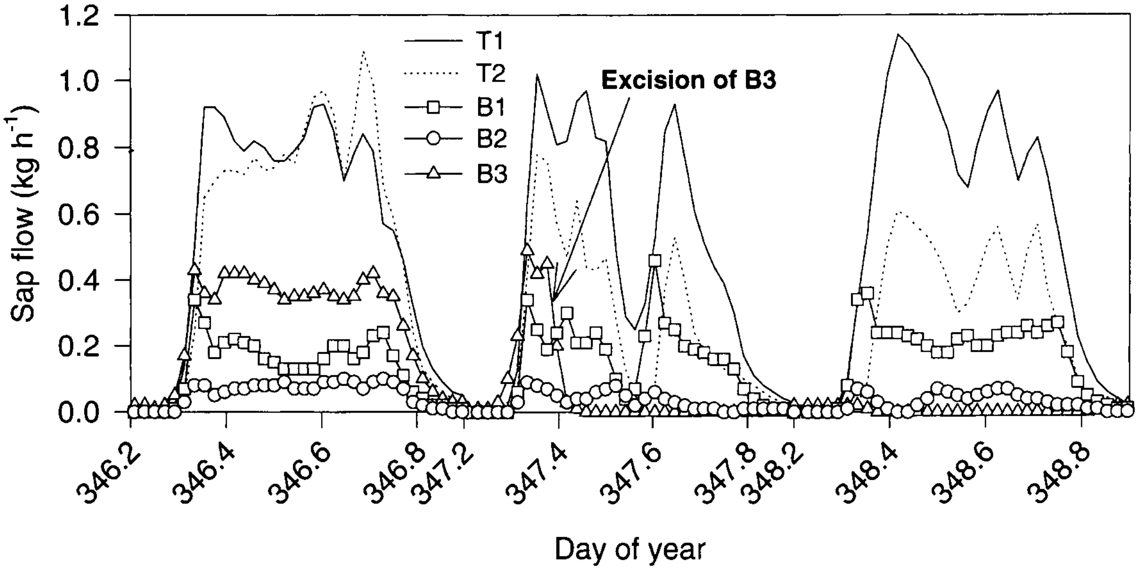

Figure 8. Responses of sap flow in branches and in trunk to the excision of branch B3 (on DOY 347). Rain occurred between 1200 and 1400 hours on DOY 347.

uptaken by the tree (Q) was very close to the total sap flow in the branches (ΣF_B), but both values were slightly lower than the calculated sap flow in the trunk (F_T). At the end of day (DOY 357), the sap flow in the trunk was about 0.5 kg higher than the sap flow in the branches (ΣF_B) and the water uptake (Q). The next morning, at the moment of excision of the remaining branches, the overall difference between these measurements was within acceptable limits ($[F_T - \Sigma F_B]/Q = 5.6$ %, $[F_T - Q]/Q = -0.2$ % and $[\Sigma F_B - Q]/Q = -5.9$ %). After excision of the branches, sap flow rapidly decreased and became nil within 15 min in the branches and in the trunk (data not shown).

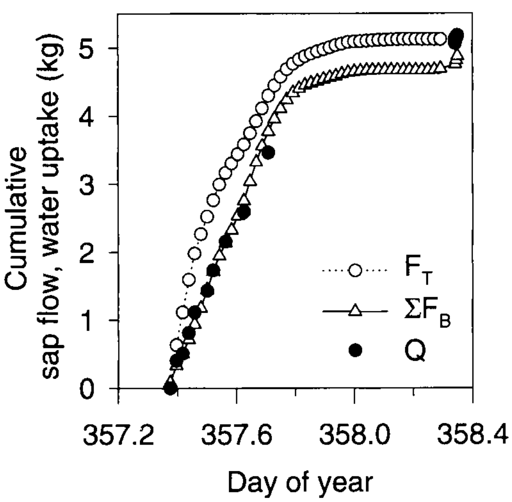

Figure 9. Comparison of cumulative sap flow in the remaining branches (ΣF_B) and in the trunk (F_T) of the 4-year-old tree compared with cumulative water uptake (Q) by the tree determined using 'cut-tree method'.

The dye investigation showed that the distribution of the staining of the cross-section was heterogeneous. To quantify the intensity and the distribution of the staining, the cross-section was objectively divided into three zones. First zone (zone I, representing 35 % of the total area) was near T1 sensor and oriented to the girdled branch B1. Second zone (zone II, 45 % of total area) was near T2 and oriented to the defoliated branch B2 and third zone (zone III, 20 % of total area) oriented to the lopped branch B3. It appeared that 51 % of the area in zone I was heavily stained (corresponding to the most active water-conducting area) while only 24 and 19 % of the area was heavily stained in zones II and III, respectively. The proportion of the not-stained area was highest in zone III (52 %, compared to 12 % in zone I and 31 % in zone II), which indicated that a large proportion of the area became non-conductive after excision of branch B3.

4. DISCUSSION

Quality of sap flow measurements using Granier's sap flux sensors mainly depends on a) the accuracy of the sap flux sensor itself which has been thoroughly studied by Granier [8, 9] and Cabibel and Do [2], and b) how well the sap flux density measured by the sensor represents the water conduction in the whole sapwood. Although the Granier's sensor demonstrated capacity of integrating sap flow over small scale [10], failure to sample a zone of sapwood with distinct sap flow from that explored by the sensor probe, could cause substantial error in total sap flow measurement using the Granier's sensors [7]. Therefore, in a case where uniformity of the sapwood characteristics is unknown, the sensor probe should explore as large a proportion of sapwood area as possible to reduce the error in calculation of the sap flow from multiplying sap flux density by sapwood area. In the present sap flow/gravimetry comparative study, trees of small diameter were used; 2-cm-long Granier sap flux probe covered more than half of the diameter of the trunk and thus the possibility of obtaining a poorly represented sap flux density measurement was minimized. This assumption was confirmed by the good correlation between sap flow and gravimetric water loss in containerized mango trees. Sap flow appeared to underestimate the gravimetric water loss by less than 10 %, which was still within the confidence intervals of the relative incertitude (10 %) of Granier's method [2]. This result from container-grown trees suggests that Granier's sap flow measuring system is sufficiently accurate for measuring water use of young mango trees.

Examination of sap flow in the trunk and in the branches of a 4-year-old mango tree under non-disturbed and disturbed conditions (canopy manipulation) permitted a further critical evaluation of Granier's method. Under non-disturbed conditions, sap flow on two opposite sides of the trunk was almost identical, which suggests that under normal conditions, circumferential variation in sap flow in mango trees of diameter of 8–10 cm may be negligible. That could be due to the isolation of the tree, the high angle of the sun in the low latitude area and the large trunk-length/diameter ratio. For trees with this range of diameter, the 2-cm-long sap flux probe covers almost half of the radius. The annulus of the outermost 2 cm of sapwood explored by the Granier's sensor represents the most active water conducting area and the majority of the total sapwood area of the trunk. The assumption that inner sapwood has an equal flux density as in the outermost 2 cm should only result in a small error in the final sap flow calculation. In the present study, good agreement between the averaged sap flow in the trunk and the total sap flow in the branches confirms this assumption. Therefore, positioning of the Granier's sap flux sensor on the trunk (orientation) is not critical for sap flow measurement in trees of diameter of 8–10 cm.

Granier sap flux sensor was found to be sensitive to both slow and abrupt alternations of the tree physiology. Leaf gas exchange of the girdled branch declined gradually after branch girdling, and such slow alteration of the plant physiology was clearly reflected by reduction in sap flow of the girdled branch. Abrupt changes in canopy transpiration induced by branch defoliation and excision were matched by immediate and rapid decline in sap flow in the corresponding branches. In addition, good agreement between branch sap flow and 'cut-tree' water uptake again demonstrates Granier's sap flux measuring system to be a valid method for measuring whole-tree transpiration in young mango tree.

Investigation of the effect of canopy manipulation on variation in branch and trunk sap flow also provided an insight into mango tree physiology. The relative stability of the whole-tree sap flow (F_B, ΣF_B) following the girdling of B1 revealed a 'compensatory effect' in the tree through certain mechanisms (e.g. increased leaf gas exchange in B2 and B3 due probably to an improvement in their water status). Although in general the xylem system is considered to be cross-connected over all sections of the trunk [19], the apparently matched decrease in sap flow in branch B1 and at T1 following the girdling of B1, and decrease in B2 and at T2 following the defoliation of B2, indicated that in mango trees the xylem system in one branch could be connected more effectively to a specific zone of xylem tissue in the trunk. As a result, whole-tree sap flow may be incorrectly integrated because of spatial variability in sap flux density in the trunk following branch manipulation. To our knowledge, this was the first time effects of branch manipulation on sap flow changes in different sectors of a trunk were studied. Cabibel and Isberie [3] studied the effects of root manipulation on sap flow changes in different sectors of a cherry tree trunk and found that the heterogeneity of sap flow in different sectors of the trunk was closely correlated with the spatial heterogeneity of soil moisture in relation to local root bundle. They concluded that preferential flow pathways existed in the soil–root–trunk system. Their results and ours together demonstrate how the canopy and/or root manipulation may alter the water transfer in the trunk and the measurement of whole-tree sap flow.

The findings of our study suggest that orchard-grown mango trees, often subjected to repeated and substantial branch manipulation such as training and branch pruning at different growth stages, may exhibit important spatial variations in water conduction in their trunks and such variations may affect the accuracy of the computation of the whole-tree sap flow. Therefore, for mango trees of large diameter, a comprehensive study of both circumferential and radial variation in sap flow in the trunk will be necessary for a reliable estimate of the whole-tree water use.

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REFERENCES

[1] Bobay V., Influence d'une éclaircie sur le flux de sève et la transpiration de taillis de châtaignier, Ph.D. thesis, Université de Paris-Sud, France, 1990, pp. 142.

[2] Cabibel B., Do F., Mesures thermiques des flux de sève dans les troncs et les racines et fonctionnement hydrique des arbres. I. Analyse théorique des erreurs sur la mesure des flux et validation des mesures en présence de gradients thermiques extérieurs, Agronomie 11 (1991) 669–678.

[3] Cabibel B., Isberie C., Flux de sève et alimentation hydrique de cerisiers irrigués ou non en localisation, Agronomie 17 (1997) 97–112.

[4] Cermak J., Deml M., Penka M., A new method of sap flow rate determination in trees, Biologia Plantarum (Praha) 15 (1973) 171–178.

[5] Chacko E.K., Physiology of vegetative and reproductive growth in mango (*Mangifera indica* L.) trees, Proceedings of the First Australian Mango Research Workshop. Cairns, Qld., Australia, 26–30 November 1984, CSIRO, Melbourne, Australia, 1986, pp. 54–71.

[6] Cohen Y., Fuchs M., Green G.C., Improvement of the heat pulse method for determining sap flow in trees, Plant Cell Environ. 4 (1981) 391–397.

[7] Goulden M.L., Field C.B., Three methods for monitoring the gas exchange of individual tree canopies: ventilated-chamber, sap-flow and Penman-Monteith measurements on evergreen oaks, Funct. Ecol. 8 (1994) 125–135.

[8] Granier A., Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres, Ann. Sci. For. 42 (1985) 193–200.

[9] Granier A., Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements, Tree Physiol. 3 (1987), 309–320.

[10] Granier A., Anfodillo T., Sabatti M., Cochard H., Dreyer E., Tomasi M., Valentini R., Breda N., Axial and radial water flow in the trunks of oak trees: a quantitative and qualitative analysis, Tree Physiol. 14 (1994) 1383–1396.

[11] Green S.R., Clothier B.E., Water use of kiwifruit vines and apple trees by the heat-pulse technique, J. Exp. Bot. 32 (1988) 221–239.

[12] Hatton T.J., Vertessy R.A., Variability of sapflow in a *Pinus radiata* plantation and the robust estimation of transpiration, Proceedings of Hydrology and Water Resources Symposium, Christchurch, New Zealand, 1989, pp. 6–10.

[13] Hatton T.J., Catchpole E.A., Vertessy R.A., Integrating of sapflow velocity to estimate plant water use, Tree Physiol. 6 (1990) 201–209.

[14] Kurian R.M., Iyer C.P.A., Stem anatomical characters in relation to tree vigour in mango (*Mangifera indica* L.), Sci. Hortic. 50 (1992) 245–253.

[15] Roberts J., The use of the tree cutting technique in the study of the water relations of mature *Pinus sylvestris* L., J. Exp. Bot. 28 (1977) 751–761.

[16] Schaffer B., Whiley A.W., Crane J.H., Mango, in: Schaffer B., Andersen, P.C. (Eds.), Handbook of Environmental Physiology of Fruit Crops, Vol. 2, Subtropical and Tropical Crops, CRC Press, Inc., Boca Raton, 1994, pp. 165–197.

[17] Steinberg S.L., McFarland M.J., Worthington J.W., Comparison of trunk and branch sap flow with canopy transpiration in Pecan, J. Exp. Bot. 41 (1990) 653–659.

[18] Steinberg S.L., Van Bavel C.H.M., McFarland M.J., A gauge to measure mass flow in stem and trunks of woody plants, J. Am. Soc. Hortic. Sci. 114 (1989) 466–472.

[19] Zimmermann M.H., Xylem Structure and the Ascent of Sap, Springer-Verlag, Berlin, 1983, 143 pp.