Kasetsart J. (Nat. Sci.) 48 : 534 - 539 (2014)

Modeling for Radial Distribution of Sap Flow in Rubber (*Hevea brasiliensis* Muell. Arg.) Trees

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ABSTRACT

This research improved the model for the radial distribution of the sap flux density in rubber trees. The objective of the study was to describe the radial variability of xylem sap flux in rubber trunks. The experiment was conducted in mature rubber trees aged 13 yr from clone RRIM 600, in a non-traditional planting area at the Chachoengsao Rubber Research Center from January to December 2007. The sap flow was measured by the heat dissipation method using home-made radial probes and then calibrated with the cut stems of rubber tree in the laboratory. The radial variability was modeled as a function of the depth into the xylem. Regression analysis was carried out using data on the sap flux density and depth into the xylem. The model used two basic assumptions: (1) young xylem (0–4 cm) has the maximum sap flux density and is stable and (2) sap flux density decreases linearly with the depth into the xylem (and thus older xylem) toward the center of the stem. The results showed that the model for radial distribution can be used to predict the sap flux density and to estimate the tree transpiration of different trunk diameters in rubber trees. The tree transpiration was highly variable with different girths of the rubber trees.

Keywords: *Hevea brasilliensis*, modeling, radial distribution, sap flow, stand transpiration

INTRODUCTION

Transpiration, as a major component of the water flow in a forest ecosystem, can be estimated at the tree and stand scale by sap flow measurement (Hatton *et al*., 1995). Sap flow methods are suited to measuring changes in the water relations, growth and water use efficiency of plants (Smith and Allen, 1996). The water flow in the trunk is mainly computed as the sap flux density (water mass per conducting area and time) and the cross sectional area of the water conducted in the sapwood. However, knowledge of the radial sap flow profile in the trunk is important to estimate the sap flux density from a single point measurement to whole tree measurement. The radial sap flow profile may vary to a large extent depending on wood anatomy and tree size

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Received date : 26/05/14 Accepted date : 18/08/14

(Granier *et al*., 1994). The error in estimating the sap flux density for individual trees based on measurement may seriously depart from the real situation in the true xylem (Hatton *et al.,* 1995). The patterns of radial variation in the sap flux density in the sapwood have been observed for many tree species (Granier *et al*., 1994; Hatton *et al*., 1995; Phillips *et al*., 1996; Lu, 1997; Lu *et al*., 2000; Ford *et al*., 2004). The radial profiles can be grouped into two types. The first showed a peak in the sap flux density about 0–4 cm beneath the cambium, while the second showed a more even profile, beyond 6 cm below the sapwood, with the profiles of both groups being similar (Lu *et al*., 2000). The maximum sap flux density appeared in the outer sapwood because the outer xylem often connects the leaves exposed to the sun whereas the low sap flux density in the deep layer of sapwood may reflect an undeveloped conducting system at the center of the stem (Nadezhdina *et al*., 2002) and the sap flow radial pattern and sapwood depth are very different in the stem and branches of trees (Nadezhdina *et al*., 2007).

The aim of this study was to describe the radial variability of the xylem sap flux in the trunks of rubber trees. The information was then used in a model of the radial sap flux density distribution to estimate the tree transpiration for different trunk diameters in rubber trees.

MATERIALS AND METHODS

Location, climate and stand

The experiment was conducted in a rubber plantation of approximately 6.2 ha that was part of the Chachoengsao Rubber Research Center (CRRC; 13.41 °N; 101.04 °E), located 200 km east of Bangkok and 69 m above sea level. The plantation consisted of rubber trees aged 13 yr from the clone RRIM 600 which is the main clone planted in Thailand. The planting pattern was 7.5 × 2.5 m and 9 × 2.5 m. The average girth of the trees at 1.80 m from the ground was 61.4 cm and the average total height was about 19.2 m. The climate at the site is tropical and humid, with an annual rainfall of 1,288 $mm.yr^{-1}$, which usually starts in March and peaks during June to August, with an average 115–385 $mm.mth^{-1}$ based on data recorded at the CRRC weather station).

Sap flow measurement

The sap flow was measured by the heat dissipation method adapted from Granier (1985, 1987) using home-made 20 mm-long radial probes that consisted of two sensor probes (needles) per set. One probe was continuously heated (0.2 W) while the other one was unheated and was used to measure the temperature of the wood tissue and to act as a reference probe. A data logger (model 21X; Campbell Scientific; Shepshed, UK) was used to collect the temperature data.

The radial variability of the sap flux density was assessed using a set of 10 cm-long probes. Each probe set was inserted at a different depth (2, 4, 6, 8 or 10 cm) into the xylem to measure the sap flux density at these different depths. A probe set was first installed at 2 cm depth on the north-facing side of the tree and the sap flux density was measured for 7 d. Then, the probe set was re-installed 2 cm deeper into the xylem every 7 d until it reached the center of the stem. The sap flux density was measured using another set of probes fixed at 2 cm depth on the opposite (south-facing) side of the same stem; this measurement was used as a reference. The radial variability of the sap flux density was studied on two trees of different girths (57.5 cm and 66.0 cm). The radial variability of the sap flux density was modeled as a function of the depth into the xylem. The model was developed according to two basic assumptions: 1) young xylem has a maximum sap flux density and (2) the sap flux density decreases linearly with depth into the xylem (and thus older xylem) toward the center of the stem. The relationship between the sap flux density and the depth into the xylem can be described by Equation 1:

$J_s/J_{s\text{-reference}} = J_{s\text{-young}}$, if $J_{s\text{-old}} > 1$ or $J_{s\text{-old}} = 1$,
$= J_{s\text{-old}}$, if $J_{s\text{-old}} < 1$ (1)

where J_s is the sap flux density, $J_{s\text{-reference}}$ is the sap flux density at a reference point of 2 cm depth into the xylem and $J_{s\text{-young}}$ and $J_{s\text{-old}}$ are the sap flux density of young xylem and old xylem, respectively. $J_{s\text{-young}}$ is defined by Equation 2:

$$J_{s\text{-young}} = 1 \quad (2)$$

$J_{s\text{-old}}$ can be expressed as a linear function of depth into the xylem and is given by Equation 3:

$$J_{s\text{-old}} = (d_1 \times D) + d_2 \quad (3)$$

where D is the depth into the xylem (measured in centimeters) and both d_1 and d_2 are empirical parameters; d_1 indicates the sensitivity of $J_{s\text{-old}}$ to D and d_2/d_1 is the depth (measured in centimeters) at which $J_{s\text{-old}}$ approaches zero.

The model was fitted to the combined data sets from two trees with d_1 = -0.1389 and d_2 = 1.568 cm. The model explained more than 97% of the variation of $J_s/J_{s\text{-reference}}$. The predicted versus observed data plot (not shown) exhibited satisfactory prediction of the model over the full range of depth into xylem studied.

Seven trees were selected for long-term monitoring from January to December 2007 of the sap flow and stand transpiration. The trunk girth at 1.8 m above the ground of the sample trees ranged from 55 to 100 cm. Sap flow probes were installed in the rubber trees. For each set of probes, two 4 cm^2 bark pieces were removed (one above the another and 10 cm apart) using a chisel. After the latex had dried, holes were drilled about 2 cm into the exposed xylem and aluminum tubes were inserted straight into the holes. The probes were then inserted into the aluminum tubes. Prior to insertion, each probe was coated with silicone grease to ensure good thermal contact, easy removal of the probe and to protect each probe from rain. The sap flux density (J_s) was calculated from Equation 4:

$$J_s = 312 \times 10^{-6} K^{1.231} \quad (4)$$

where J_s is the sap flux density (measured in liters per decimeter per hour) and K is the sap flow index calculated from Equation 5:

$$K = \frac{\Delta T_o - \Delta T_i}{\Delta T_i} \quad (5)$$

where ΔT_o is the daily maximum and ΔT_i is the current temperature difference (measured in degrees Celcius) between the two sensors of the probe. The tree transpiration (measured in liters per day) was calculated using Equation 6:

$$\text{Tree transpiration} = J_s \,.\, A \quad (6)$$

where J_s is the sap flux density (measured in liters per decimeter per hour) and A is sapwood area of each ring (measured in decimeters).

RESULTS

Radial profiles

Two different radial profiles were obtained from the first tree (No.1, girth of 66.0 cm) with a larger girth and from the second tree (No.2, girth of 57.5 cm) with a thinner trunk (Figure 1). The model for radial distribution was capable of predicting the sap flux density of a rubber tree. The sap flux density at a depth of 0–4 cm below the trunk surface was high and stable. Then, the sap flux density started to decrease below 4 cm depth into the xylem toward the center of the stem. However, the model underestimated the higher assimilation rate (Figure 2).

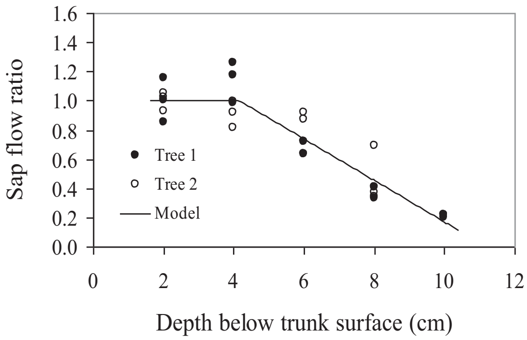

Figure 1 Radial sap flux density of two rubber trees. Tree 1 is a large tree (66.0 cm girth) while tree 2 is smaller (57.5 cm girth). The sap flux density was averaged over at least 7 d for each depth.

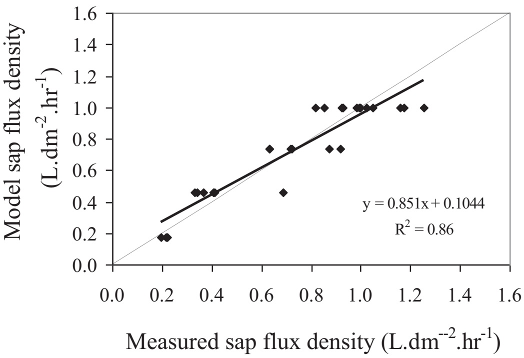

Figure 2 Relationship between sap flux density measured and simulated by the model for 7 d. The solid line indicates the regression between sap flux density measured and stimulated by the model for 7 days. The dotted line indicates a one-to-one ratio between the two parameters. The model was fitted as a function of relative depth into the xylem (correlation coefficient (R^2) = 0.86). The sap flux density at 2 cm was considered as a reference.

Tree transpiration

Daily tree transpiration was calculated for seven rubber trees over a period of 7 d using the radial distribution model. The tree transpiration and sap flux density varied with the different girths of the trees (Figure 3 and Table 1). When the canopy was fully expanded, tree transpiration in the larger trees was highest at approximately 162.67–192.80 $L.d^{-1}$. In contrast, in the smaller diameter trunks, tree transpiration was lower at about 45.15–64.07 $L.d^{-1}$.

DISCUSSION

This research produced an improved model of sap flux density. The model showed that the sap flux density of young xylem (outer xylem) was high and stable whereas the sap flux density of old xylem (inner xylem) decreased linearly toward the center of the stem. Patterns of radial variation in the sap flux density of the sapwood have been observed in many tree species (Granier *et al*., 1994; Hatton *et al*., 1995; Phillips *et al*., 1996; Lu, 1997; Lu *et al*., 2000; Ford *et al*., 2004). The radial profiles can be grouped into two types. The first showed a peak in sap flux density about 0–4 cm beneath the cambium. The second showed a more even profile, while beyond 6 cm below the sapwood, both groups of profiles were similar (Lu *et al*., 2000). The maximum sap flux density appeared in the outer sapwood because the outer xylem often connects the leaves exposed to sun whereas the low sap flux density in the deep

Table 1 Cross sectional area at 1.80 m height above the ground and mean sap flux density calculated on tree transpiration of seven rubber trees on 1 March 2007.

	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Tree 6	Tree 7
Girth (cm)	100.00	81.00	78.50	65.00	63.00	60.50	55.00
Radius with bark (cm)	15.92	12.89	12.49	10.35	10.03	9.36	8.75
Bark thickness (cm)	0.70	0.70	0.70	0.70	0.70	0.70	0.70
D_{max} (cm)	15.22	12.19	11.79	9.65	9.33	8.93	8.05
Coefficient ($J_s/J_{s\ ref}$ × Area)	535.42	389.48	370.27	267.21	252.30	233.90	194.65
Mean sap flux density ($L.dm^{-2}.h^{-1}$)	1.50	1.40	1.70	1.14	1.27	1.60	0.75
Tree transpiration ($L.d^{-1}$)	192.80	131.20	151.49	73.70	77.49	90.15	55.44

D_{max} = Radius without bark J_s = Sap flux density, $J_{s\text{-}reference}$ = Sap flux density at a reference point of 2 cm depth into the xylem.

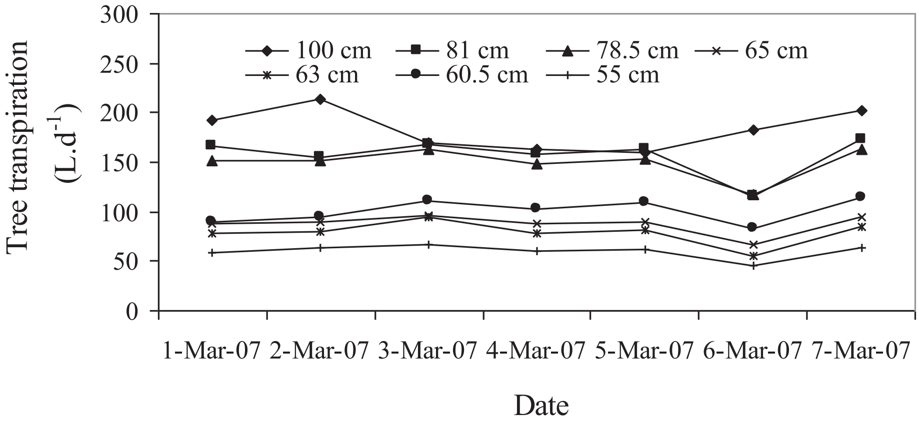

Figure 3 Tree transpiration of seven rubber trees of different girths for a 7 d period.

layer of the sapwood may reflect an undeveloped conducting system at the center of the stem (Nadezhdina *et al*., 2002) and the sap flow radial pattern and sapwood depth were highly different in the stem and braches of the trees (Nadezhdina *et al*., 2007).

The sap flux density and tree transpiration changed with tree size with the sapwood area increasing with increasing stem diameter. For large trees, the sap flux density was higher in the outer sapwood area. In contrast, the sap flux density decreased dramatically in the inner sapwood. These results were similar to Philips *et al.* (1996) who reported a reduction in the daily sap flux density between the outer sapwood and sapwood at a depth of 20–40 mm.

CONCLUSION

A model of radial xylem sap flux density profiles was devised on the basis of data from representative trees using the total sapwood area. The sap flux density at 0–4 cm below the trunk surface was high and stable but then decreased beyond 4 cm depth into the xylem. The radial variability of the sap flux density was modeled as a function of the depth into the xylem. The sap flux density and tree transpiration varied strongly in rubber trees of different girth.

ACKNOWLEDGEMENTS

The study was funded by the Thai-French Committee for Training, by CIRAD and by Burapha University and Kasetsart University. The authors thank the French Embassy in Bangkok for supporting the bilateral fellowship and the Department of Agriculture (DOA) at the Chachoengsao Rubber Research Center (CRRC) for allowing access to the rubber plantation and to some equipment used in this research. Many thanks are also recorded to the French CIRAD researchers and the Thai partners from Kasetsart University and the CRRC.

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