Research Article

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Seasonal changes in xylem sap flow rate in mature rubber plants

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Abstract

The rate of flow of xylem sap of mature rubber tree was recorded round the clock continuously for two years using a Granier type thermal dissipation probe (TDP). The measurements were made on 19 year old trees of the clones, RRII 5 and PR 255 with a mean girth of 78 and 82 cm, respectively at 150 cm above bud union. Overall, the average rate of water mining by a tree was to the tune of 22 ± 3 L day^{-1}. The diurnal and seasonal differences in the sap flow rate were very evident which responded to the ambient weather conditions such as intensity of sunlight, temperature, rainfall *etc*. In the morning hours, as the sunlight intensity increased there was a corresponding sharp increase in sap flow rate which attained maximum level around mid-day. In the evening, as the light intensity declined, the sap flow rate also declined. The maximum rate of sap flow per day was recorded in December and the minimum in February coinciding with complete defoliation of the canopy. Taking a mean water consumption of 22 L tree^{-1}day^{-1} and assuming there are 400 trees ha^{-1}, the water consumption works out to be in the range of 1-2 mm day^{-1}. This is significantly lesser than the potential evapo-transpiration (ET) of an open field in this traditional region. Taking the long-term average rain fall in the region (3000 mm year^{-1}), it can be seen that the water loss due to transpiration (T) by the trees amounted only to 11 per cent of the annual rainfall.

Keywords: Hevea brasiliensis, sunlight intensity, water use, xylem sap flow

Introduction

Natural rubber plant (*Hevea brasiliensis*) is a perennial woody tree being cultivated mainly for the product cis-isoprene polymer, *i.e.*, rubber, by tapping the tree's soft bark tissue enriched with laticiferous tissue. The measurement of whole plant water use especially in woody plants like natural rubber tree is rather difficult considering the huge canopy and complex environmental responses. The quantum of water loss in a tree depends on canopy size, physiological condition and soil and atmospheric factors. There is also an increasing interest in water and carbon fluxes at the canopy-atmosphere interface in the perspective of global climate change scenario.

Sap flow measurement is a precise technique to study the tree water relations and to quantify whole-plant water use. They are used, for instance, to estimate whole tree transpiration or to evaluate water stress periods due to climate condition, diseases or damages. Moreover, sap flow measurements are useful to assess the physiological response of trees to environmental factors and changing climate. Estimation of transpirational water loss is a direct method for accounting the water use of individual tree. Granier (1985) developed a dual-probe sap-flow measuring system which is known as thermal dissipation probes (TDP). The TDP probe method has been popular among tree physiologists as it is simple and more reliable

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compared to other methods (Lu *et al.*, 2004). Sap flow measurements can provide an accurate method for determining the transpiration from a single tree. Moreover, sap flow can be monitored continuously over long periods (Granier and Loustau, 1994; Allen and Grime, 1995).

So far, there are not enough published experimental data on water use of rubber plantations in traditional rubber growing area and hence worthy to study it thoroughly with an advanced sap flow measurement technology. The water use linked evaporative loss of vegetation consists of two components, first one is plant transpiration (T) and the second one is direct evaporation from the soil and surface of other organic matter (E). The present work is aimed at to quantify the water flux in a mature rubber plantation using TDP probes. The study is also leading to analyze the seasonal transpiration water loss in a traditional rubber growing area by relating xylem sap flow rate with environmental parameters like temperature, rainfall and sunshine intensity. The water use of rubber plantations using the experimentally collected sap flow data is also worked out in this study.

Materials and methods

Experimental site and plant material

The experimental site was located at Rubber Research Institute of India (RRII), Kottayam, Kerala at an altitude of 72 MSL, longitude 76° 34’ E and latitude 9° 32’ N. The xylem sap-flow rate was measured in three trees (n=3) each of two rubber clones namely RRII 5 and PR 255 of 19 years old with a mean girth of 78 and 82 cm, respectively at 150 cm above bud union. The terrain was with gentle slope and the soil was laterite. The rubber plants were planted during 1987 with 4.5 metre spacing between the trees. Granier’s TDP probes with 80 mm length were inserted in to the main trunk at breast height and the probes were connected to a programmable data logger (DL 2, Delta T Devices, UK).

Measurement of sap flow

Sap flow was measured by Granier’s method (Granier, 1985), based on the computation of thermal dissipation of two probes inserted into the xylem. Probes consist of two needles, each one incorporating a T-type thermocouple. The upper probe is heated and its temperature is compared to lower ambient temperature needle. A broad band of thin plastic film was wrapped around the inserted probes to avoid stem transpiration. The data in milli volt (mV) signal was downloaded every weekend and transferred to spread sheets. Further, the signal was converted to flow velocity (V). Sap flow is a function of temperature difference: it reaches the maximum (dTM) when sap flow is close or near to zero and it decreases as water comes up. The sap flow is calculated by an equation that takes into account this empirical relation. Granier proposed empirically the sap flow velocity as

$V = 0.0119 * K^{\wedge 1.231}$ cm s^{-1} where, K = (dTM-dT)/dT

where, dT is the measured difference in temperature between that of the upper heated needle referenced to the lower non-heated needle and dTM is the value when there is no sap flow or the lowest flow in a day.

The sap flow velocity can be converted to sap flow rate (mL hr^{-1})

$Fs = As * V * 3600$ mL hr^{-1}

where, Fs is the sap flow and As is the cross-sectional area of sap conducting wood (cm^2).

Rubber tree belongs to diffuse porous wood (Reghu *et al*., 2006). The average active xylem area was estimated to be 30 per cent of cross sectional area. Fs is a direct measurement of transpiration water loss for a given time. Generally, the rate of tree transpiration depends on stem temperature, soil moisture availability and phenological phases. The daily flow rate was averaged for every month and the mean value indicating per day flow rate was calculated. Relationships between sap flow rate and T_{max}, sunlight intensity and cumulative sunlight load were established in different seasons of the year by simple linear regression analysis.

Meteorological observations

The daily meteorological parameters *viz.* maximum temperature, rainfall and potential evaporation (mm day^{-1}) were collected from meteorological observatory of RRII, Kottayam, India which is situated 200 m away from the experimental plot. The average annual rainfall was around 3000 mm. The air temperatures for summer and winter seasons were recorded in the range of 33-35 °C (T_{max}) and 23-24.5 °C (T_{min}) and 32-34 (T_{max}) and 21-22.5 °C (T_{min}), respectively. The cumulative visible light load at the canopy level was measured by a solar radiation measurement system (EMCON, India). The solar light measurement system comprised photosynthetic active radiation (PAR) sensors, control unit and memory module. The incident sunlight recordings were downloaded fortnightly and computed in spread sheets. It was in a range of 1200–5000 x 10^4 µmol m^{-2} day^{-1} in different seasons. These parameters were used for establishing environmental relationships with the sap flow rate.

Results and discussion

Diurnal change in sap flow pattern

The sap flow rate of mature rubber trees followed a definite diurnal pattern on sunny days (Fig. 1). The flow rate increased as the sunshine intensity increased during morning hours and it declined during afternoon indicating that the flow rate is regulated by stomata movement. A minimum value of 1-20 mL water hr^{-1} during night and to a maximum value of 3 L water hr^{-1} during mid-day was recorded in a given day. The sap flow rate was as low as 5.5 L $tree^{-1}$ day^{-1} during wintering season (defoliation period) and as high as 40 L $tree^{-1}$ day^{-1} during December, just before the onset of defoliation (Table 1). Sap flow measurement is a direct account of water use of tree species through transpiratory water movement. Generally, xylem sap flow rate has been used for direct estimation of transpiration rate in woody species (Ortuno *et al*., 2005) as the sap flow through xylem is a measure of transpiratory pull. Similar trend of diurnal course of sap flux has been observed in many tree species and compared (Granier *et al*., 1996; Meiresonne *et al*., 1999). Different trees have distinctive sap wood area and observations showed values as high as 30 kg hr^{-1} (Granier *et al*., 1996) in huge tree species. The variation among the rain forest tree species were corroborated with their difference in canopy size and age of the trees.

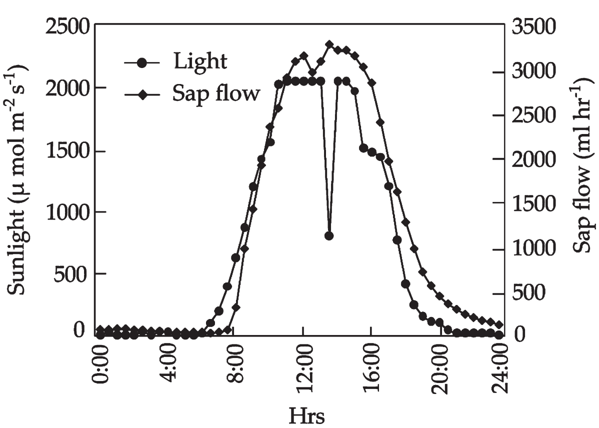

Fig. 1. Typical diurnal xylem sap-flow pattern in mature rubber trees. The sap flow rate was continuously measured by Granier's type thermal dissipation probes (TDP). Diurnal sunlight intensity (µmol m^{-2} s^{-1}) and same time sap flow (mL hr^{-1}) rate are depicted

Table 1. Mean daily sap-flow rate (L day^{-1}) in two clones of mature *H. brasiliensis* trees

Month	Mean sap-flow rate (L day^{-1}) RRII 5	PR 255
January	28.5 ± 1.0	30.0 ± 0.7
February	14.0 ± 0.6	5.5 ± 0.4
March	16.0 ± 0.7	12.0 ± 0.4
April	21.0 ± 0.7	9.5 ± 0.4
May	16.0 ± 0.8	17.0 ± 0.5
June	13.0 ± 0.5	13.0 ± 0.7
July	14.0 ± 0.7	19.0 ± 0.8
August	21.5 ± 0.8	21.0 ± 0.9
September	22.0 ± 1.4	17.0 ± 1.1
October	34.0 ± 1.0	30.5 ± 1.0
November	28.0 ± 1.3	24.0 ± 1.5
December	40.0 ± 1.5	32.0 ± 1.1

± SE indicated, mean of all days of month

Sap flow rate during wintering and refoliation period

As rubber is a deciduous tree, every year the tree sheds leaves with the onset of winter, followed by the sprouting of new flush of leaves. The wintering phenomenon in *Hevea* generally starts from later part of December and intensive during January. The sap flow rate was recorded corresponding defoliation and refoliation periods (Fig. 2). With the progression of defoliation period the sap flow rate declined drastically from 40 L water $tree^{-1}$ day^{-1} (during last week of December) and at the end of defoliation period it was 5.5 to 14 L water $tree^{-1}$ day^{-1}. The flow rate started increasing concomitant with the onset of new flush of leaves which was in 3rd week of January and attained

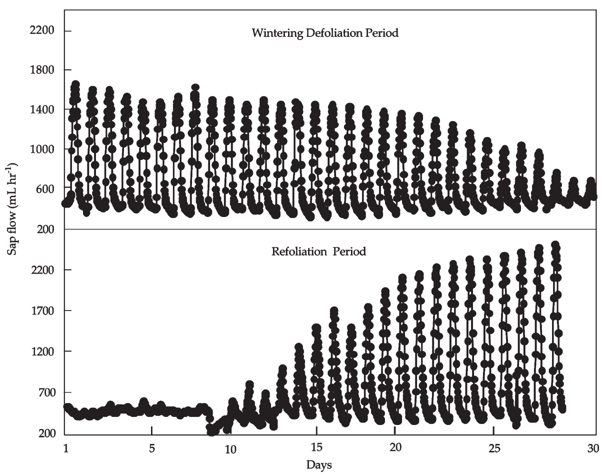

Fig. 2. Xylem sap flow pattern in mature rubber trees during defoliation (January) and refoliation period (February)

optimum flow rate after 3rd week of February. This observation clearly supports the fact that the rate of sap flow is directly proportional to the canopy leaf area (LA) and stomatal conductance (Prazak *et al*., 1994).

Seasonal changes in sap flow rate

The daily xylem sap flow rate of rubber trees for an entire year is depicted in Figure 3. The day to day water mining pattern of the tree showed a huge variation in different seasons. It was low during the beginning of the year which coincided with defoliation period. There was a subsequent gain in the flow rate during refoliation period. The flow rate again declined during March owing to prevailing higher atmospheric air temperature coupled with soil moisture deficit. With the onset of summer rainfall, the sap flow rate increased due to the recharging of soil moisture. During April to July the sap flow rate was in the range of 15 to 20 L water tree^{-1} day^{-1}. The flow rate increased from August onwards and attained a peak rate of 35 to 40 L water tree^{-1} day^{-1} during October to December when the canopy was full of mature leaves. The North-East monsoon and post-monsoon period witnessed higher water consumption by a mature rubber tree. This was mainly due to good sunlight intensity in the morning hours followed by rain fall in the afternoon that provided saturated level of soil moisture with better transpiration pull in this season. The available photosynthetic source area per plant was the highest during the post-monsoon season in rubber plants (unpublished data). The transpiration rate is directly proportional to leaf area, stomatal frequency and soil moisture (Prazak *et al*., 1994). Similar studies conducted in forest and agro-forest tree species showed that sap flow rate is controlled by soil moisture and sunlight intensity in spruce and eucalyptus (Dye 1996; Montero *et al*., 2001).

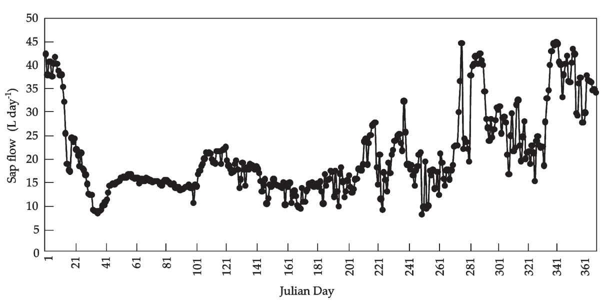

Fig. 3. Daily sap flow rate (L day^{-1}) in a mature rubber plantation at RRII, Kottayam. The day of the year is indicated (Julian day)

Factors influencing sap flow rate

Sap flow rate of a given tree is directly proportional to stem girth as natural rubber tree is diffuse porous wood, the amount of xylem vessels distributed depends on the cross sectional area (Reghu *et al.*, 2006). The observations revealed that the flow rate also depends on the number of branches and total leaf area, *i.e.*, canopy size (data not shown). The major environmental factors which regulate the sap flow rate are solar radiation, sunshine hours, temperature variance, atmospheric vapour pressure deficit (VPD) and soil moisture conditions. Sunlight intensity had a direct role in regulating the sap flow rate. There was a positive relationship between light intensity and sap flow rate (Fig. 4A). The diurnal xylem flow rate on a sunny day was directly controlled by the sunlight intensity (R^2=0.6- 0.75 in April and May). On a given day, the rate of decline in the sap flow with respect to reduction in sunlight intensity in the late afternoon was lower than the rate of increase in sap flow with increase in the light intensity in the morning hours. Even during the mid day, when there was a sudden decline in sunlight intensity due to a passing cloud, sap flow rate did not show any concomitant reduction (Fig. 1) indicating that the water movement in the xylem is uninterrupted by any temporary shade condition. Obviously the cumulative sunlight load on daily basis had a positive influence upon the daily transpiration water loss (Fig. 5).

Significant positive relationship existed between day time temperature and sap flow rate during pre-monsoon period (Fig. 4B). By and large, the T_{max} (maximum temperature) did not have any strict influence on the rate of xylem flow throughout the year probably due to cumulative effect of many factors. Sap flow rate during the summer was lower than post-monsoon season (Fig. 3). During summer season the prevailing high atmospheric VPD might have further aggravated by high air temperature (RRII, Kottayam meteorology data) and low soil moisture leading to stomatal closure. When stomatal conductance sharply decreases (low xylem water potential) invariably leads to a reduction in transpiration rate. In general, during dry summer period sap flow can undergo a considerable reduction as stomatal conductance (gs) is influenced by soil moisture content (Welander and Ottosson, 2000). Interestingly intensive rainy days also witnessed a sharp decline in sap flow rate most probably due to cloudy days leading to partial closure of stomata. In a comparative study with many plant species it has been reported that woody species are more directly influenced by variation of climatic factors than other forest species (Granier *et al*., 2000).

Water use of rubber plantations

Continuous two years observation of sap flow rate in 18-19 year old rubber trees indicated that a

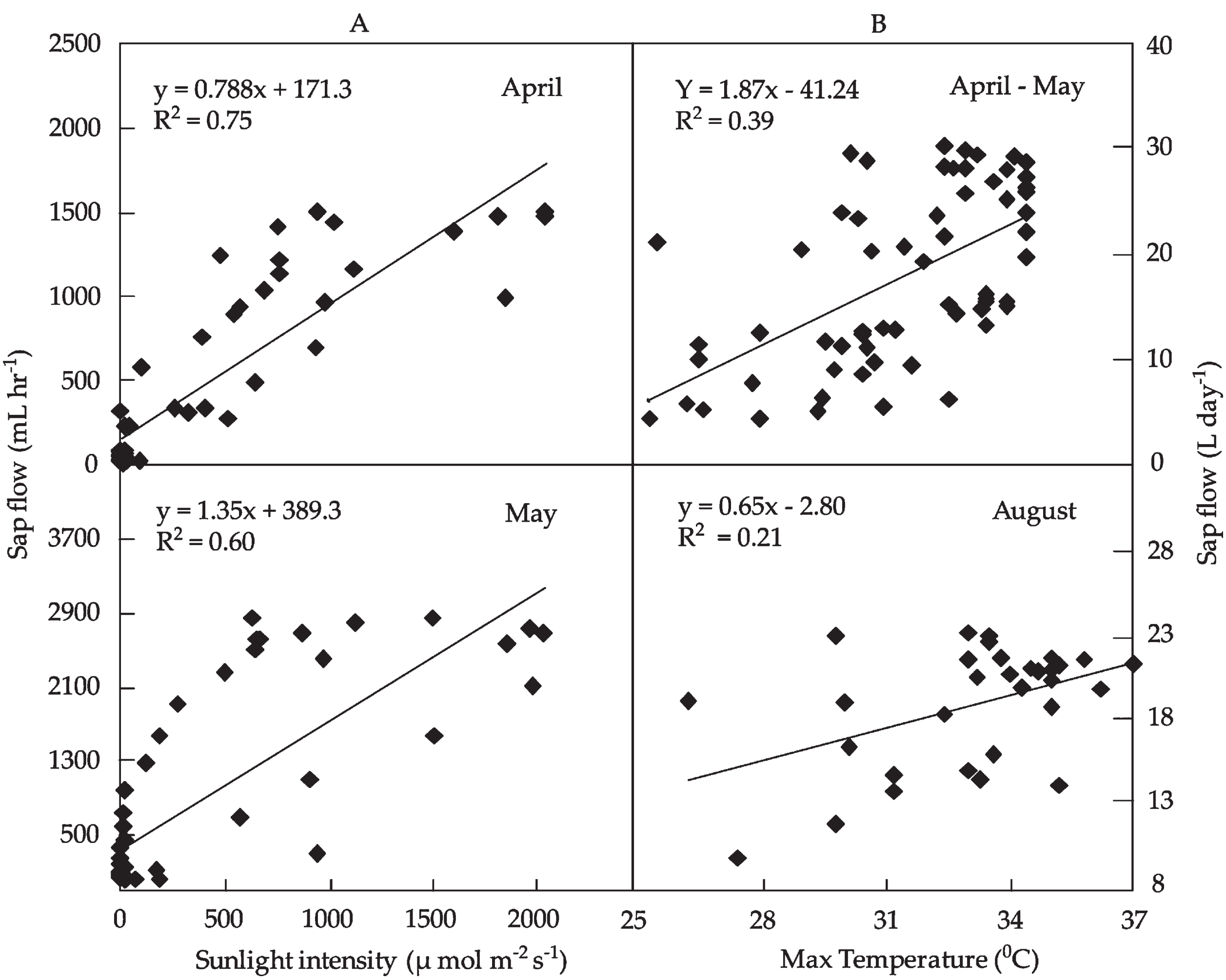

Fig. 4. Relationship between (A) sunlight intensity (µmol $m^{-2}s^{-1}$) and same time sap flow rate (ml hr^{-1}) and (B) maximum temperature (T_{max}) and sap flow rate (L day^{-1}) in mature rubber trees

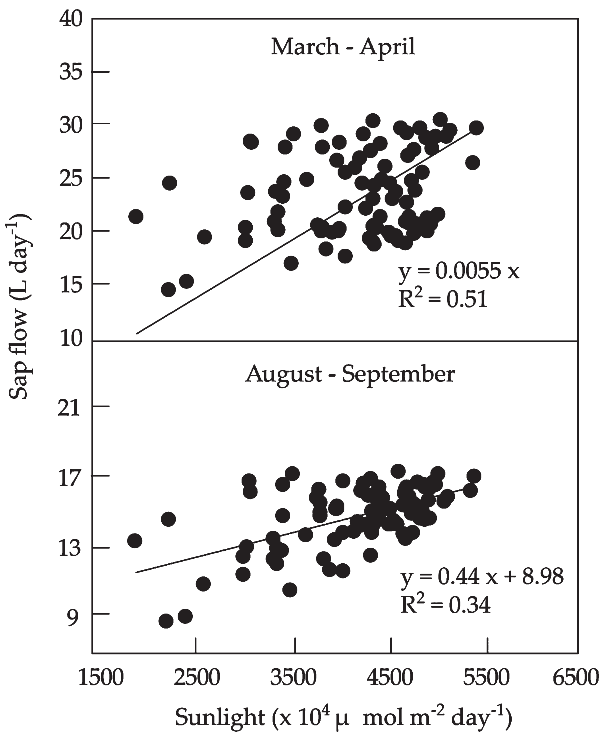

Fig. 5. Relationship between daily cumulative sunlight load (x 10^4 µmol m^{-2} day^{-1}) and sap flow rate in mature rubber trees during summer and monsoon months

mature tree mined an average of 22 L water $tree^{-1}$ day^{-1}. Average tappable tree stand in traditional rubber growing area is around 400 trees ha^{-1}. Considering the average field stand the mean water consumption of rubber plantation is

$$22 \times 400 \times 365 = 3.2 \times 10^6 \quad L\ ha^{-1}\ year^{-1}$$

Mean annual rainfall of Kottayam area is around 3000 mm

$$= 3 \times 10^7 \ L\ ha^{-1}\ year^{-1}$$

The water consumed by rubber plantation as estimated from sap flow rate was around 11 per cent of the rainfall. The amount of water transpired by a mature tree was around 1-2 mm day^{-1}. A previous report from Sri Lanka showed that the estimate of transpiration by the sole rubber crop was exceptionally low (5mm per week) in a two year old young rubber plantation (Rodrigo *et al*., 2005). The seasonal changes in transpiration water movement had been reported in mature rubber plants. Observations on transpiration rate of mature rubber tree in North East Thailand indicated that the sap flow rate declined from 1.6 mm to 0.4 mm day^{-1} as the dry season progressed (Isarangkool Na Ayutthaya *et al*., 2009). Earlier studies with lysimetric method in traditional rubber growing areas in South India showed that mean plant and surface evapotranspiration was 4.4 mm day^{-1} (Jessy *et al*., 2002). Under field condition the evapotranspiration of mature rubber plants varied from 2-6 mm as reported from different countries (Monteny *et al*., 1985; Gururaja Rao *et al*., 1990; Jessy *et al*., 2004). During drought months, a maximum evopo-transpiration rate of around 3-4 mm day^{-1} has been recorded in 10 year old rubber plantation in India (Gururaja Rao *et al*., 1990). From the present and earlier studies with Penman-Monteith equation for water use of rubber plantation, it is understood that an approximately same amount of water equal to the sap flow rate may be lost from the soil surface as evaporation. Hence, the total plant and surface evapo-transpiration loss of water is about 20-25 per cent of the rainfall received.

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