International Journal of Plant Production 1(2), September 2007
ISSN 1735-6814
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Influence of environmental factors on the sap flux density of mango trees under rain-fed cropping systems in West Africa

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Accepted 5 June 2007; Published online 20 July 2007.

Abstract

Xylem sap flux density (F_d) was measured, on a 43-year-old (mature) and three 4-year-old (young) mango (*Mangifera indica* L.) trees, using Granier-type probes. The relative influences of environmental variables were examined under well-watered condition. Circumferential variation in F_d was also investigated by placing sensors on the north, south-west and south-east sides of the mature tree. Sap flux density lagged solar radiation (R_s) by 30 min and led vapour pressure deficit (D_e) also by 30 min in the young trees whereas F_d lagged R_s by 60 min in the mature tree. However, the canopy of mature tree seems better coupled with the diurnal course of D_e as time lag between the paired series was zero. Maximum F_d occurred at 1330 h in the mature tree and 1130 h in the young trees. Significant (P<0.001) correlation was between most of the environmental factors and F_d for mango tree. No systematic differences in F_d were found between the north and other aspects (sides) of the mature tree. Instead they had close relation with each other (r^2> 0.98). However, F_d from the south-west side of the 43-year-old tree was 4.2% and 18.3% higher on a typically bright and partially clouded days while F_d from south-east side was lower with about 4.4% and 1.1%, respectively, compared with F_d on the north. This indicates the possibility of transpiration enhancement in response to wind advection from the nearby village in the south-west direction. Identification of the relative influence of these environmental factors on sap flow may provide basis for an in-depth analysis of the control of transpiration in rain-fed mango trees both under plantation and agroforestry systems in West Africa.

Keywords: Mango; sap flux density; environmental variables; canopy interactions; West Africa.

Introduction

Mango *(Mangifera indica* L.*)*, a diffuse-porous species and one of the most important tropical tree crops (Lu et al., 2000), belongs to the family Anacardiaceae (Morton, 1987). Mango is drought tolerant and could be conveniently cropped under rain-fed conditions. However, supplemental irrigation may be required for optimising growth; fruit set and yield

(Lu and Chacko, 1997). Poor and unreliable flowering is one of the factors leading to low productivity (Leonardi et al., 1999), but applying irrigation from peak flowering (full bloom) to fruit maturity could induce reliable flowering leading to high yield (Schaffer et al., 1994, Lu and Chacko, 1998). Pre-flowering irrigation was reported to increase the overall photosynthetic activity of the tree at the time of flowering (González et al., 2004). The necessity for direct and continuous monitoring of water use for precise irrigation scheduling in mango orchards has been reported (Lu and Chacko, 1997, Lu and Chacko, 1998).

In West Africa mango trees are either left in agricultural fields as a form of agroforestry practise or cropped in large plantations. However, despite current advances in developed countries, there is little or no information regarding mango water use and/or its canopy interaction with the ambient physical environment either in plantation or under agroforestry systems. Currently the effects of changing environmental variables (soil, water and atmospheric conditions) on water use by trees are poorly understood in most part of Africa. Better understanding of the mechanisms by which trees respond to these factors will be necessary for accurate assessment and management of local, regional and global water budgets in relation to climate changes (Bovard et al., 2005). Others have reported highly species-specific sap flow responses to radiation and humidity deficits (Oren and Pataki, 2001). Measurements of whole-ecosystem water flux can provide important information on field scale response to environmental variables (Greco and Baldocchi, 1996), but are limited in the information they provide on biological mechanisms regulating theses processes (Bovard et al., 2005). In this study meteorological measurements combined with sap flow estimations provide a low-cost option to study the effects of changing atmospheric conditions on canopy physiological response on a continuous basis. Therefore, the main objective was to examine the degree to which different real-time climatic factors influence mango tree canopy process via its effect on xylem water uptake under sub-humid tropical conditions. A few previous studies have reported radial variations in the rates of water movement in xylem tissue, but little is reported on azimuthal variations (Lu et al., 2000; Ewers and Oren, 2000; Kobuta et al., 2005). Therefore, in addition to the above objective, the effect of changing atmospheric conditions on sap flux density measured from different aspects of tree trunk was examined.

Materials and methods

Study sites

This experiment was conducted in a 2.43 ha of 4-year-old mango trees predominantly of cv. Palmer, located at the summit of *Kotokosu* watershed, 15 km east of Ejura (07°20´N, 01°16´W; elevation≈210 m) and within the forest-savannah transition zone of Ghana. A 43-year-old tree was located in a maize field about 150 m away from the young orchard. The study area is characterized by distinct wet and dry seasons with long-term (1973-1993) mean annual rainfall of 1260 mm, most of which falls from April to October. Maize was planted between rows of young and around the big mango trees. Stem diameter was measured with a diameter tape. Tree height and crown diameter were measured with a Spiegel relaskop (Relaskop-Technik, Austria). Leaf area index (LAI) was measured at eight points under the canopy of the individual selected trees with the SunScan canopy analysis system (Delta-T Devices, Cambridge, UK). Mean values were computed by averaging all individual estimates of LAI under each tree. Sapwood thickness was measured with a core sampler and was used to estimate tree sapwood area (SWA).

Meteorological and sap flow measurements

Meteorological variables, such as incoming solar radiation (SP-LITE pyranometer, Kipp & Zonen, Delft), air temperature (50Y Temperature probe, Vaisala, Finland), relative humidity (50Y Relative humidity, Vaisala, Finland), wind speed and direction (A100R Anemometer, vector instrument, UK), were sampled at 10-s intervals and recorded as 10-min averages with a CR10X datalogger (Campbell Scientific, Inc., USA).

Sap flow was measured with the temperature difference method of Granier (1987). Two, 30-mm long (with 20-mm heating zone) cylindrical probes, 2 mm in diameter, were implanted in the sapwood of the tree trunks with previously installed aluminium tubes and are vertical separated by 12 cm. The probes were installed on the north side of the trees (also on the south-west, 240^o from the north side; and south-east, 120^o from the north side of the mature mango tree) to minimise direct heating from sunshine, and then shielded with aluminium foil against rainfall. The downstream probe (the upper coil) was continuously heated with a constant power source of 200 mW while the unheated upstream probe (the lower coil) served as a temperature reference. During conditions of zero sap flow, the temperature difference between the lower and the upper probes represents the steady state temperature difference caused by the dissipation of heat into non-transporting sapwood. Signals from sap flow sensors were scanned every 30-s and 30-min means were recorded (DL2e with double ended mode, Delta-T Devices) from each sensor. Sap flux density was computed with the empirical relationship validated for different species (Granier, 1987, Lu and Chacko, 1998) as:

$$F_d = 42.84\left(\frac{\Delta T_{\max} - \Delta T}{\Delta T}\right)^{1.231} \qquad (1)$$

where F_d is average sap flux density integrated over the probes length (g cm^{-2} h^{-1}), ΔT is the temperature difference observed between the heated and reference needles, and ΔT_{max} is the value of ΔT when sap flow is zero, which is generally taken as the peak nighttime value of ΔT.

Measurements were conducted on three young mango trees and one mature tree but with sensors places round the trunk at 120° interval (from the north side) on the circumference. Data used in this study were measured from DOY (day of the year) 221-DOY 227, and DOY 262-DOY 273. The biometric parameters (stem diameter, bark thickness, tree height, and leaf area index and sapwood area) of the gauged trees are given in Table 1.

Table 1. Tree height (TH), stem diameter (SD), bark thickness (BT), sapwood area (SWA) and leaf area index (LAI) of a 43-year-old and three 4-year-old mango trees in Ghana.

Allometric	43-year-old	4-year-old		
parameters		1	2	3
Tree height (m)	11.5	3.62	4.13	3.63
Stem diameter (cm)	71.6	11. 5	12.2	12.0
Back thickness (cm)	4.2	0.5	0.8	0.8
Sapwood area (cm^2)	2140.4	85.4	86.2	84.2
Leaf area index (-)	8.07±1.46	3.31±0.45	4.08±1.10	3.86±0.75

Statistical analysis

All statistical analyses were made with SPSS procedures (Version 10.0, SPSS, San Rafael, CA). Relationships between sap flux density (F_d, g cm^{-2} h^{-1}) and all the atmospheric conditions were explored with correlation and regression analyses. Cross-correlation function was used to determine the possible time shift between solar radiation (R_s), vapour pressure deficit (D_e) and F_d time series. Non-linear curve fits were performed in SIGMAPLOT 8.02 (SPSS, San Rafael, CA)

Results and discussion

The daily course of R_s and D_e for the two measurement periods are shown in Figure 1. In August (DOY 221-227), diurnal courses of both solar radiation and vapour pressure deficit were slightly lower, but more varied, compared to the September period (i.e. DOY 262-273). Generally, the conditions were characterized by high humidity, light winds with frequent overcast due to monsoon clouds typical of the wet season of West Africa (Jegede, 1997; Oguntunde and van de Geisen, 2005).

Mean diurnal F_d series of the young trees (dashed line) for measurement period in August and its standard deviation are shown together with that of the mature tree (solid line) in Figure 2. The overall mean diurnal sap flow for the young trees varied between 1.88 litres day^{-1}, at mid-night, and 33.4 litres day^{-1}, shortly before the mid-day (1100 h). While the overall mean diurnal sap flow for the mature tree varied between 8.49 litres day^{-1}, at mid-night to 47.50 litres day^{-1} at 1330 h. The water movement pattern showed a rapid rise in sap flow from sunrise to the peak and thereafter remains constant until around 1700 h before steeps out to near zero flow after the sunset in the 4-year-old trees. The pattern is somewhat different in the 43-year-old tree, where sap flow rise to the peak after the midday (1330 h). The vertical bar showing the standard deviation gives an indication that sap flow varied more during the daytime and especially at peak periods. Apart from period during hours 18-22 when the value of F_d is lower for young trees compared to older one, flow velocities observed in young trees were consistently higher than the matured tree.

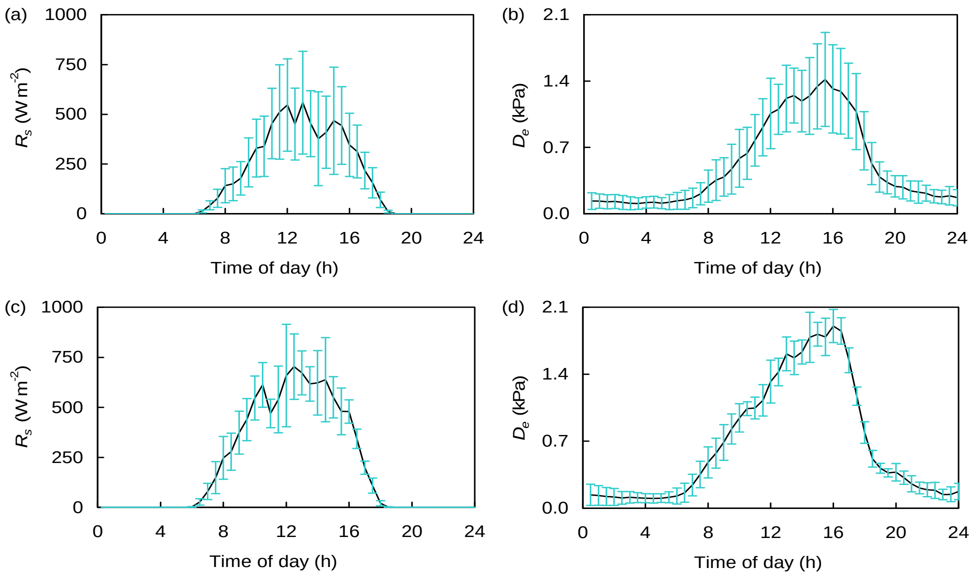

Figure 1. Average diurnal pattern of solar radiation (R_s) and vapour pressure deficit (D_e) for meteorological measurements between (a&b) DOY 221-227; and (c & d) DOY 261-273 in 2002 at Ejura, Ghana. Vertical bars show standard deviation.

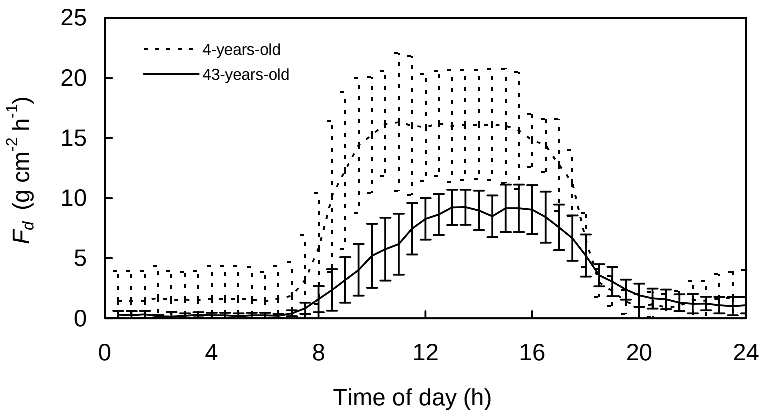

Figure 2. Mean diurnal sap flux density (F_d) pattern of 43-year-old mango tree (thick line) and 4-year-old trees (short-thin line) over the measurement periods (vertical bars represent ± standard deviation).

The influence of R_s on F_d for both the young and mature mango trees is shown in Figure 3. Nearly, high r^2 was observed for both cases, with a tendency toward light saturation at high R_s, which is more pronounced with the mature mango tree. The canopy response showed to R_s

is partly due to the effect of radiation on stomatal opening. Similarly, a positive correlation was found between D_e and F_d for both young and mature trees. The performance of the regression models (linear, polynomial and exponential) fitted was compared using r^2 and RMSE. Simple polynomial showed the best result with r^2 ranging from 0.70-0.85 (Table 2). The highest r^2 of 0.85 was estimated between F_d and D_e of the mature tree. This indicates that the leaf of this tree was more coupled to the diurnal course of D_e than the young trees. The scatter noticed on these plots (Figure 3) showed a possibility of time lags or shifts between R_s, D_e and F_d. A cross-correlation analysis was carried out on these paired series. Sap flux density lagged solar radiation (R_s) by 30 min and led vapour pressure deficit (D_e) also by 30 min in the young trees whereas F_d lagged R_s by 60 min in the mature tree. The result of time lag estimation further confirm that the canopy of mature tree was more coupled with the diurnal course of D_e as time lag between the paired series was zero. In addition, the estimated time lag coupled with the observed discrepancies in the diurnal course (time of maximum sap flow occurrence) of F_d (Figure 2) may be connected with the hydraulic resistance-capacitance in the flow path. Previous studies (Goldstein et al., 1998; Meizer et al., 2001) have shown similar pattern in which bigger trees tend to exhibit peak F_d latter than smaller trees because bigger trees have higher water storage capacities along the soil-plant atmosphere flow path leading to more delay in the response of stem water uptake to a step change in the canopy demand. Meizer et al. (2001) observed, in a tropical moist forest, that maximum F_d near the tree base occurred at 1400 h in the largest trees and 1130 h in the smallest trees with diameter at breast height accounting for > 90% of the variation in the time of day at which maximum F_d occurred. They concluded in agreement with Goldstein et al. (1998) that the shared relationship between time of maximum F_d and tree size suggest that a common relationship exists between diurnal stem water storage capacity and tree size. The result of this study is consistent with this recent hypothesis that allometric scaling of plant vascular systems and water use is universal.

Table 2. Regression statistics to compare the relative performances of different functions of sap flux density (F_d) with solar radiation (R_s) and vapour pressure deficit (D_e) for 43-year-old and 4-year-old mango trees in Ghana.

Tree age	Relation-ships	Model type: Linear		Polynomial		Exponential	
		r^2	#RMSE	r^2	RMSE	r^2	RMSE
43-year-old	$F_d = f(R_s)$	0.64	1.63	0.70	1.32	0.46	2.61
	$F_d = f(D_e)$	0.72	1.34	0.85	0.87	0.51	1.97
4-year-old	$F_d = f(R_s)$	0.63	2.34	0.73	1.64	0.48	2.53
	$F_d = f(D_e)$	0.67	1.51	0.77	1.23	0.53	2.12

#-RMSE is root mean square error, the smaller the value the better the model.

To analyse the effect of atmospheric conditions on the circumferential variations in F_d, data obtained from the 43-year-old tree was further analysed in that respect. Firstly, F_d was correlated with meteorological variable and the result is presented in Table 3 (correlation with the mean F_d of the young trees is also included). Correlation between F_d and the five meteorological variables were generally similar with respect to the sensor aspects (north, south-west and south-east). Highest r values were observed for humidity followed by temperature. Wind direction showed the lowest but significant ($P<0.001$) r especially on the south-east side. To further explore this azimuthal effect, two days were selected based on their clearness/cloud conditions i.e. DOY 221 (a bright day) and (b) DOY 222 (a partially clouded day). Figure 4 showed the diurnal course of sap flux density (F_d) at the three aspects in the mature mango for DOY 221 and DOY 222 as well as the linear relationships between F_d on the north side (*x*-axis) and F_d on south-west and south-east sides (*y*-axis). The daytime maximum was slightly lower and more perturbed on the partially clouded day. On both days, peak F_d were attained after the noontime.

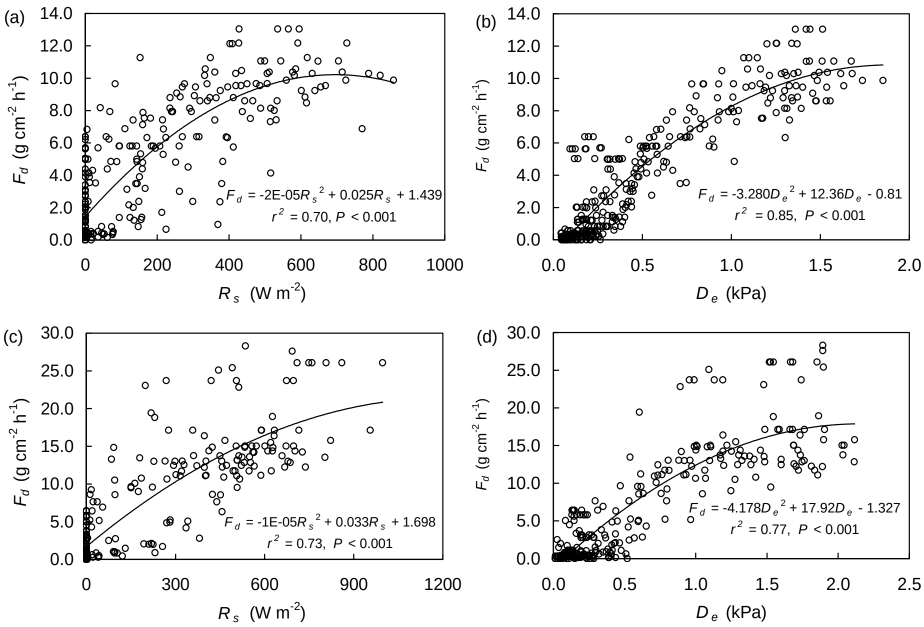

Figure 3. Relationships between diurnal sap flux density (F_d) and (a) solar radiation (R_s) (*b*) vapour pressure deficit (D_e) for mature mango tree; (c) solar radiation (R_s) and (*d*) vapour pressure deficit (D_e) for young mango trees in Ejura, Ghana.

Table 3. Correlation coefficients (*r*) between sap flux density on different aspects (north, south-east and south-west) of big mango tree and on the northern aspect of the young mango trees in Ejura, Ghana.

Environmental Variable	Correlation coefficients (*r*)			
	43-year-old			4-year-old
	north	south-east	south-west	north
Solar radiation (R_s)	0.808	0.814	0.789	0.816
Air temperature (*T*)	0.922	0.903	0.915	0.796
Relative humidity (H_r)	-0.925	-0.906	-0.919	-0.819
Wind speed (*U*)	0.547	0.562	0.527	0.505
Wind direction (U_d)	0.346	0.304	0.380	0.134*

*Significant at $P = 0.038$ while all other are significant at $P<0.001$.

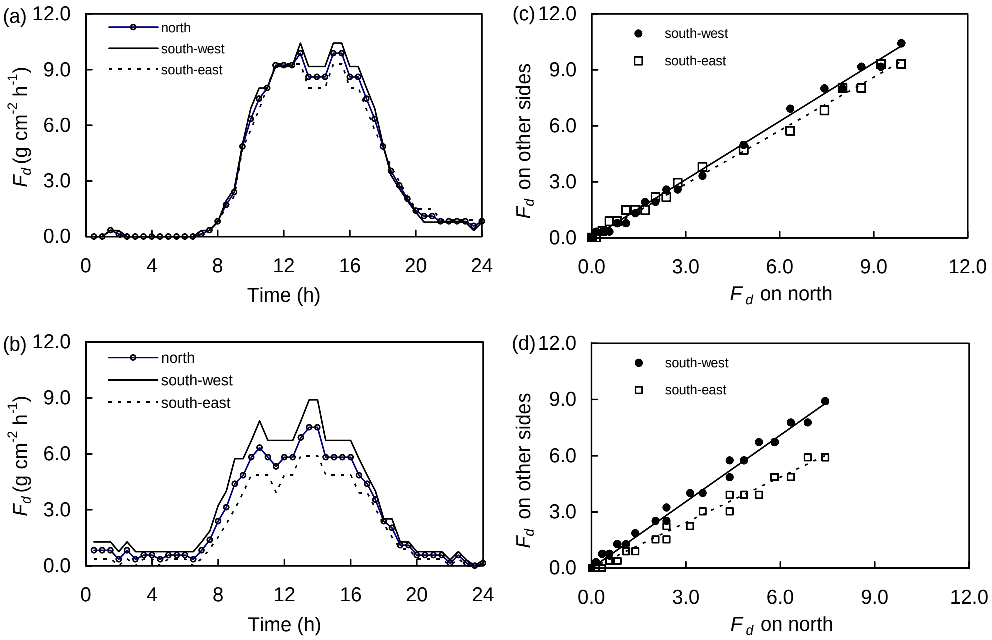

Figure 4. Diurnal course of sap flux density (F_d) at three aspects in the mature mango tree for (a) DOY 221 (a bright day) and (b) DOY 222 (a partially clouded day). (c & d) Showed the linear relationships between F_d on the north side (*x*-axis) and F_d on south-west and south-east sides (*y*-axis).

Linear relationships showed a highly correlated (r^2>0.98) F_d on all the aspects considered. The F_d from the south-west side of the 43-year-old tree was 4.2% and 18.3% higher on a typically bright (DOY 221) and partially clouded (DOY 222) days while F_d from south-east side was lower with about 4.4% and 1.1%, respectively. However, the discrepancies between F_d on the north and other sides were not significant on the bright (P=0.22) and the partly clouded (P=0.30) days. But there was a statistically significant difference (P<0.027) between F_d on south-west and south-east aspects on the partly clouded day. Higher values of F_d on south-west side may be connected to the impact of advected energy from a nearby village (100 m away), which was directly located on this side of the tree. A rose plot (not shown) of the wind source for the DOY 221 and 222 indicated that wind came mainly from the south-west direction on these two days.

It was therefore noted that monsoon clouds, coupled with wind advection played a role in circumferential variation in F_d on this site. Although compared to radial variations in F_d in the trunk, which have been extensively studied, there has been little research on azimuthal variation (Kubota et al., 2005), our result showed that wind direction/advection and cloud could cause azimuthal variations in F_d. Others have reported that circumferential differences are due to solar heating or sun exposure (Granier, 1987; Lassoie et al., 1977).

Furthermore, other factors that may influence variation in circumferential F_d include row structures and horticultural practices (Lu et al., 2000). Nevertheless, F_d measured on the north side seems to be similar with other aspects under the two sky conditions and therefore a reasonable aspect to measure sap flow in trees.

In conclusion, sap flow technique was combined with meteorological applications to study the effects of changing atmospheric conditions on canopy physiological response for identification of the relative influence of the environmental factors on sap flux density, which may provide basis for an in-depth analysis of the control of transpiration in rain-fed mango trees both under plantation and agroforestry systems in West Africa.

Acknowledgements

Logistics during data collection was provided through the GLOWA Volta project (Grant number 07GWK01) while at Center for Development Research, Bonn, Germany.

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