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Water use pattern and canopy processes of cashew trees during a drying period in West Africa

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Abstract

Water flux in a young, 4-year old, cashew (*Anacardium occidentale* L.) plantation was studied over a dry season, from November 2001 to March 2002, in the forest-savannah transition zone of Ghana, West Africa. The temperature-difference method was used over this five-month period to quantify the diurnal and day-to-day whole-tree sap flow (Q_t) and hence the canopy scale transpiration (E_c). Measured allometric data were used to convert sap flow to canopy transpiration, while the observed meteorological variables were used to derive canopy scale conductance (g_c) by inverting the Penman-Monteith equation. Sap flow varied between 9 and 22 kg day^{-1} and was on average Q_t = 14 kg day^{-1} for the entire period. Tree sap flow was closely dependent on solar radiation and less dependent on air vapour deficit. Using no time shift, sap flow was fitted to a simple equation that showed its parabolic response to global radiation. The estimated average diurnal pattern of g_c ranged from 0.1 to 2.2 mm s^{-1} while aerodynamic conductance (g_a) ranged from 21.9 to 49.3 mm s^{-1}. This result is expected to be of value in the analysis of atmospheric control of canopy transpiration in orchards in West Africa.

Keywords: Sap flow; Water use; Cashew trees; Stomata conductance; Aerodynamic conductance; West Africa.

Introduction

In semi-arid regions, characterised by water scarcity and unreliable rainfall, proper water management strategies for optimum production for agriculture and other water needs are important. The Volta basin in West Africa is one of such regions characterised with rural poverty and increased population pressure (Andreini et al., 2000). Studies related to sustainable water use in general, and agricultural water management in particular, are of priority importance in order to increase production without degrading the basin's resources. Changes in land use lead to changes in water use as evaporation from each component of the land surface is controlled by different factors. These different factors influence both evaporation from the soil and plant transpiration whereby the former is a purely physical process and the latter is also affected by physiological responses (Allen and Grime, 1995). Available models, well validated with measured independent data, are needed for efficient management of land and water resources and as sub-models for general or regional circulation models (Stannard, 1993; Dolman et al., 1993). Part of the data needed is whole-tree water use, which will help hydrologists to resolve issues of water resource management, to evaluate the role of transpiration in forest and woodland hydrology and to quantify the water requirements of short-rotation forests (Cienciala and Lindroth, 1995; Loustau et al., 1996; Barrett et al., 1996; Wullschleger et al., 1998).

During the 1980s, sap flow gauges, which use a temperature difference principle were developed by Granier (1985, 1987) and have been successfully used by different researchers since then (Phillips et al., 1997). This method provides a simple, relatively inexpensive but robust means of continuous measurement of whole plant sap flow and helps to measure transpiration from different species or a single component of mixed vegetation (Granier et al., 1996). A problem with this approach is that sap flow lags somewhat behind transpiration because of the capacitance of the trunk and branches (Granier and Loustau, 1994; Phillips et al., 1997). Measured sap flows have successfully been used to derive canopy conductance by inversion of the Penman-Monteith equation (Cienciala et al., 2000; Wullschleger et al., 2000; Lagergren and Lindroth 2002; Oguntunde, 2005).

In the 2001/2002 dry season, sap flow measurements were taken in Ejura, Ghana (West Africa), in a southern part of Volta basin, with the objective of obtaining direct and independent estimates of transpiration from the woody component of the vegetation in the watershed. The measurements were made as part of the on-going GLOWA Volta project, a research project designed to study “sustainable water use under changing land use, rainfall reliability, and water demands in the Volta basin”. This study was to examine the day-to-day and diurnal patterns of the cashew tree water use and canopy conductance under a drying soil water condition.

Materials and methods

Study Site

The experimental site was located within a 4-year old cashew plantation of about 90 hectares belonging to a private farmer in a small watershed 15 km east of Ejura, Ghana. In the savannah areas of West Africa, and especially in Ghana, cashew plantation is increasingly cultivated mainly because it is drought tolerant, grows well on marginal lands and for its forex earnings potentials (Rehm and Espig, 1991; Yidana, 1996). This watershed (Latitude 07° 20′ N and Longitude 01° 16′W) forms the southern pilot site of the Glowa Volta project (www.glowa-voilta.de). The area lies in the forest-savannah transition zone, and is mainly composed of farming communities with agricultural practices, ranging from subsistence to large-scale commercial farming. Cultivation of tree crops, with special attention to cashew is currently increasing. The climate is sub-humid with a long, bimodal, wet season lasting from April to October, which alternates with a relatively short dry season that lasts from November to March. Long-term mean annual rainfall is about 1.26 m. Tree density was 175 trees per hectare and average canopy cover was estimated to be about 25%.

Sap flow and meteorological measurements

A representative experimental plot of 50 m x 100 m in the area was selected in the middle of the plantation. Sap flux density in trees was measured using the temperature difference (*TD*) method (Granier, 1985; 1987). The method uses heated and unheated thermocouple pairs. The set-up consists of a pair of fine-wire copper-constantan thermocouples connected such that voltage measured across the copper leads represents the temperature difference between the thermocouples. Two cylindrical probes, about 2mm in diameter, were implanted in the sapwood of the tree trunk with previously installed aluminium tubes, separated vertically by 12-15 cm apart at breast height (about 1.3 m was used in this study). Each of the probes contains a 2 cm long copper-constantan thermo-element with copper heating coil. Tubes are filled with a heat conductive paste in order to obtain good thermal contact with the probes. Probes were installed on the north side of the tree, to minimise direct heating from the sunshine, and then shielded with aluminium foils against rainfall. The sensors were connected to the power source and a data logger following the manufacturer's prescriptions (UPGmbH, 2001). The upper heating coil dissipates heat into the sapwood and the sap flow surrounding the probe while the lower is unheated. During conditions of zero sap flow density, such as night time, 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. This maximum *TD* value serves as the baseline from which any increase in sap flow causes a decrease in *TD*. The following equation (Granier, 1985; 1987) was used to compute the sap flux density (f, ml cm^{-2} min^{-1}) where TD_m is the baseline (maximum) temperature difference for the data set or the day. Sap flow data were sampled at 30 s intervals and averaged and recorded every 30 minutes. Whole-tree sap flow and canopy transpiration were calculated from flux density using sapwood area and tree density following UPGmbH (2001).

$$f = 0.714\left[\left(\frac{TD_m}{TD}\right) - 1\right]^{1.231} \tag{1}$$

Meteorological variables such as incoming solar radiation, net radiation, air temperature, wind speed and direction, relative humidity and rainfall, were scanned at 10-s and recorded as 10-min averages with an automatic weather station installed within the cashew plantation. A total of six trees with about the mean of the diameter size distribution were selected for sap flow measurements. A non-linear regression equation was used to fit a relationship between water use (kg h^{-1}) and the incoming solar radiation using the Levenberg-Marquardt algorithm to optimize the parameters (Marquardt, 1963).

Biometric measurements

Fifteen trees were randomly selected within the 0.5 ha experimental plot. Stem diameter at breast height (1.3 m) was measured with a diameter tape. Tree height was measured with Spiegel relaskop (Relaskop-Technik, Austria), while bark thickness was determined with a small ruler. Sapwood thickness was manually measured with a core sampler. Tree sapwood area was estimated from stem diameter, sapwood thickness and bark thickness. Leaf area index (LAI) was measured with a SunScan canopy analysis system (Delta-T Devices, Cambridge, UK). LAI was measured at eight points under the canopy of the individual selected trees. Mean value was computed by averaging all the individual estimates of LAI.

Stomata and aerodynamic conductance

The canopy conductance was estimated by inverting the Penman-Monteith equation (Granier and Loustau, 1994).

$$\frac{1}{g_c} = \left[\frac{\Delta}{\gamma}\left(\frac{A-\lambda E_c}{\lambda E_c}\right)-1\right]\frac{1}{g_a}+\frac{\rho_a}{E_c}\frac{C_p}{\lambda\gamma}VPD \tag{2}$$

where g_c (m s^{-1}) is the canopy conductance, Δ (kPa K^{-1}) is the rate of change of vapour pressure with temperature, γ (kPa K^{-1}) is the psychrometric constant, ρ (kg m^{-3}) is the density of the dry air, C_p is the specific heat capacity of the air (J kg^{-1} K^{-1}), *VPD* is the vapour pressure deficit (kPa), g_a is the boundary layer conductance (m s^{-1}), λ is the latent heat of water vaporization (J kg^{-1}), E_c is the canopy transpiration (kg m^{-2} s^{-1}) and A is the available energy at the canopy level (J m^{-2} s^{-1}). Aerodynamic conductance (g_a) was calculated from wind speed using the equation (Granier et al., 2000).

$$g_a = \frac{k^2 u}{\ln\left[(z-d)/z_0\right]^2} \tag{3}$$

where u is the wind speed (m s^{-1}) and z is the wind measurement height(m). The zero plane displacement (d) and the roughness length (z_0) were taken as 0.75 and 0.1 of the tree height (=4.2m), respectively; k is the von Karman constant (=0.41). Available energy was estimated according to Granier and Loustau (1994). Half-hourly estimates of g_c were calculated using all the variables specific to those time steps while daily g_c was based on the daily average of all the variables.

Results and discussion

Climatic variables

Daily mean meteorological parameters for the period between middle of December 2001 and end of March 2002 are shown in Fig.1. Average air temperature was fairly constant throughout the period and the precipitation was quite scanty typical of a dry season in West Africa. Temperature ranges from 20-27 °C with the lowest value during harmattan (northeast trade wind) period in January 2002. Total rainfall events recorded in the weather station was 19.5 mm. The highest mean daytime solar radiation was observed in March, with 505.4 Wm^{-2} and the lowest in January (169.9 W m^{-2}), when the atmosphere is dry and dusty as a result of harmattan. Low values of humidity were observed during the months of January and February while the highest daily value of vapour pressure deficit (VPD = 2.95

kPa) was recorded on DOY 40 (February 9, 2002). Wind speed showed progressive slight increases (Figure 1d), with the highest value (2.37 m s^{-1}) recorded in month of March. Mean diurnal patterns for these entire variables are presented in Figure 2. Solar radiation peaked around mid-day (1230 hour) while the maximum diurnal *VPD* was observed about 2 hours later (1430 hour). Air temperature (Figure 2b) showed a similar trend as *VPD*, whereas humidity showed an inverse pattern to temperature. On a typical day, the maximum value of wind speed is recorded two to three hours before mid-day.

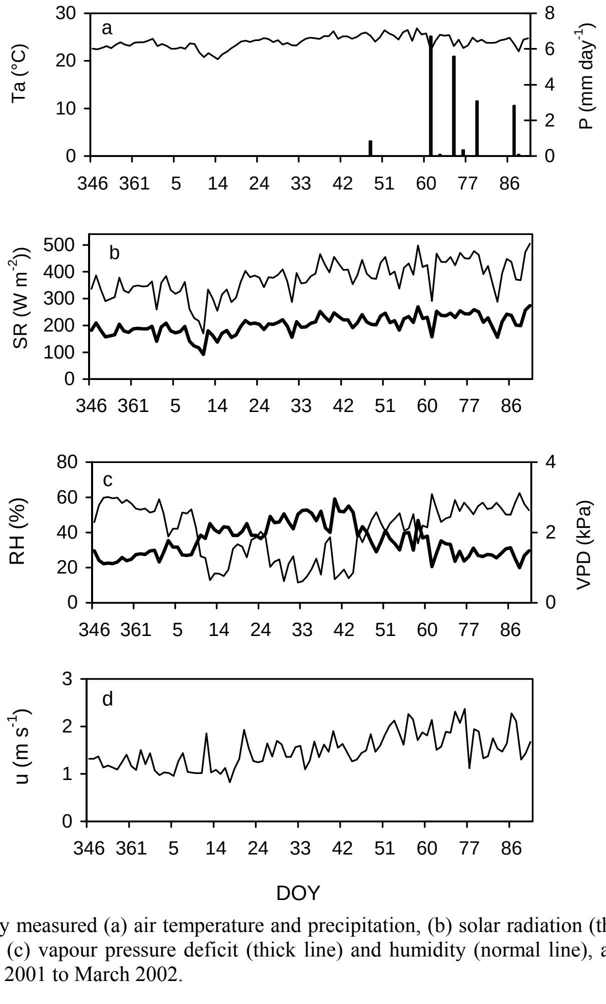

Figure 1. Average daily measured (a) air temperature and precipitation, (b) solar radiation (thick line for daytime, i.e. SR > 0, average,), (c) vapour pressure deficit (thick line) and humidity (normal line), and wind speed for a period from December 2001 to March 2002.

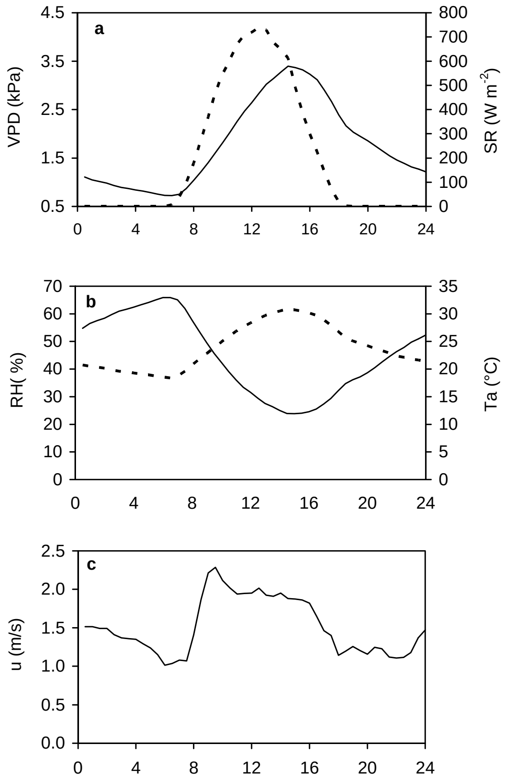

Figure 2. Average diurnal pattern of (a) vapour pressure deficit (solid line) and solar radiation (dashed line), (b) humidity (solid line) and temperature (dashed line), and wind speed (measured about 2m above the tree canopy).

Tree biometric relations

Stem diameter at breast height for the fifteen sampled trees ranged from 10.8 to 20.0 cm; with an average of 14.55 cm. Three trees were selected for sap flow measurement as they represent the average diameters of the sampled trees. Tree height varied between 3.9 and 5.3 m, basal area between 91.6 and 314.2 cm^2, and sapwood area between 71.9 and 225.2 cm^2. A power relationship was fitted for the fifteen trees and a relationship between sapwood area (SA) and stem diameter at breast height (DBH) is presented in Figure 3a. The coefficient of determination, R^2=0.981, for the relationship was highly significant. Similarly, a linear relationship was observed between sapwood area and basal area (BA). The regression line (Figure 3b) has a slope of 0.68, intercept of 4.92 and R^2 of 0.982. A clear trend between SA and BA did not cross zero, possibly because the relationship keeps changing as the tree develops heartwood. Teskey and Sheriff (1996) observed a similar relation between SA and BA in *Pinus radiata* trees.

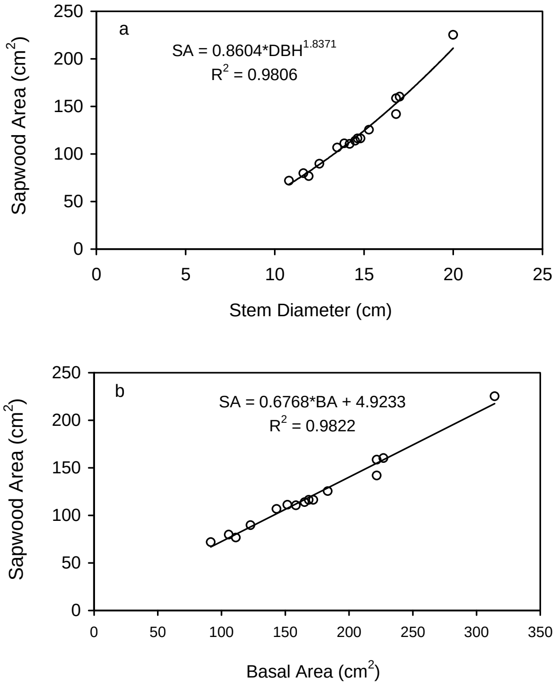

Figure 3. Relationship between sapwood area (SA) and (a) stem diameter (DBH), and (b) basal area (BA) of the fifteen sampled trees.

Whole-tree sap flow and canopy transpiration

Average sap flow density on sapwood area basis for the gauged trees is illustrated in Fig. 4. At the onset of the dry season in November 2001 (DOY 319-328), the maximum half-hourly sap flux observed ranged from 12.4 to 16.4 g cm^{-2} h^{-1}. In December (DOY 335-344), the observed maximum sap flux increased and varied between 15.9 and 24.4 g cm^{-2} h^{-1}. This range slightly decreased (15.7-21.4 g cm^{-2} h^{-1}) in January 2002 (DOY 12-21), partly because of changing environmental variables due to harmattan condition prevailing during this period. Consistently low values were observed during the peak of the dry season in February (DOY 50-59) and March (DOY 77-86). The values ranged from 8.3 to 11.9 g cm^{-2} h^{-1}, and 6.9 to 10.9 g cm^{-2} h^{-1} for the two months respectively. Mean diurnal data for the 47 days measurement period and its standard deviation are shown in Fig. 5. The overall mean diurnal water use varied between 0.94 litres day^{-1}, during mid-night, and 37.3 litres day^{-1}, shortly before the mid-day (between 10-11am). The water use pattern shows a rapid rise in sap flow from sunrise to the peak and thereafter steeps out to near zero flow after the sunset. The vertical bar showing the standard deviation gives an indication that sap flow varied more during the daytime and especially at peak periods. Tree transpiration was estimated from sap flow using the sapwood area and tree density. Observed daily transpiration ranged from 0.37 to 0.93 mm day^{-1} with overall mean of 0.58 ±0.15 mm day^{-1}. Higher values were observed in December/January and lower values in February/March. Averages in January and December showed that more water was been transpired than averages in November, February and March. To ascertain whether there are significant differences within the periods studied, mean differences of the periodic transpiration were compared using student t test and the LSD post-hoc test. The results of the test are shown in Table 1. All the values for November, December and January were significantly different ($P < 0.0001$) when paired against February and March. All other pairs were not significant ($P > 0.05$). Generally, transpiration declined as the soil column dries out. This observation showed similar values for the first three months (November-January) and thereafter a sharp decrease. This may be connected to physiological requirements of the crop during flowering and fruit developments, which occured during this period.

Sap flow showed a closer relationship with the solar radiation and very little concordance with the vapour pressure deficit of the ambient air. Average diurnal course of transpiration, *SR* and *VPD* were used to show these relationships in Fig. 6. Time shift between the observed sap flow peak and *SR* was approximately 2 hours while it was about 4 hours in case of *VPD*. Sap flow was closer with *SR* than with *VPD*. A simple equation that relates a parabolic response of tree water use to incoming solar radiation without any time lag considerations was fitted. The equation is of the form where Q_t is sap flow rate (kg h^{-1}), *SR* is solar radiation (W m^{-2}), *a* and *b* are fitted parameters.

$$Q_t = \frac{aSR}{b + SR} \tag{4}$$

Data set from DOY 50-55 and DOY 77-80 were used to calibrate the non-linear regression model (Eq. 4) and validation was done with DOY 56-59 and DOY 81-86 respectively. Both the results of the curve fitting and the validation are shown in Fig. 7. The coefficient of determination (R^2) of the fitted equation was 0.87 and 0.91 when tested with independent datasets. *SR* was responsible for about 90 % of the variations in Q_t. Inclusion of a function of vapour pressure deficit or humidity, using a form of equation presented by Cienciala et al. (2000) contributed only insignificantly to the R^2. Parameters “a” and “b” were found to be 1.14 kg h^{-1} and 92.76W m^{-2} (units were derived dimensionally). It was noted from Fig. 7a, that sap flow responded to radiation almost linearly from sunrise and reached a threshold value at which the rate of change starts to decrease until finally the response becomes insignificant to any further change in radiation. Others have also found significant relationship between Q_t and *SR*, either with time lag (Hinckley et al., 1994), or without (Köstner et al., 1992; Cienciala et al., 2000).

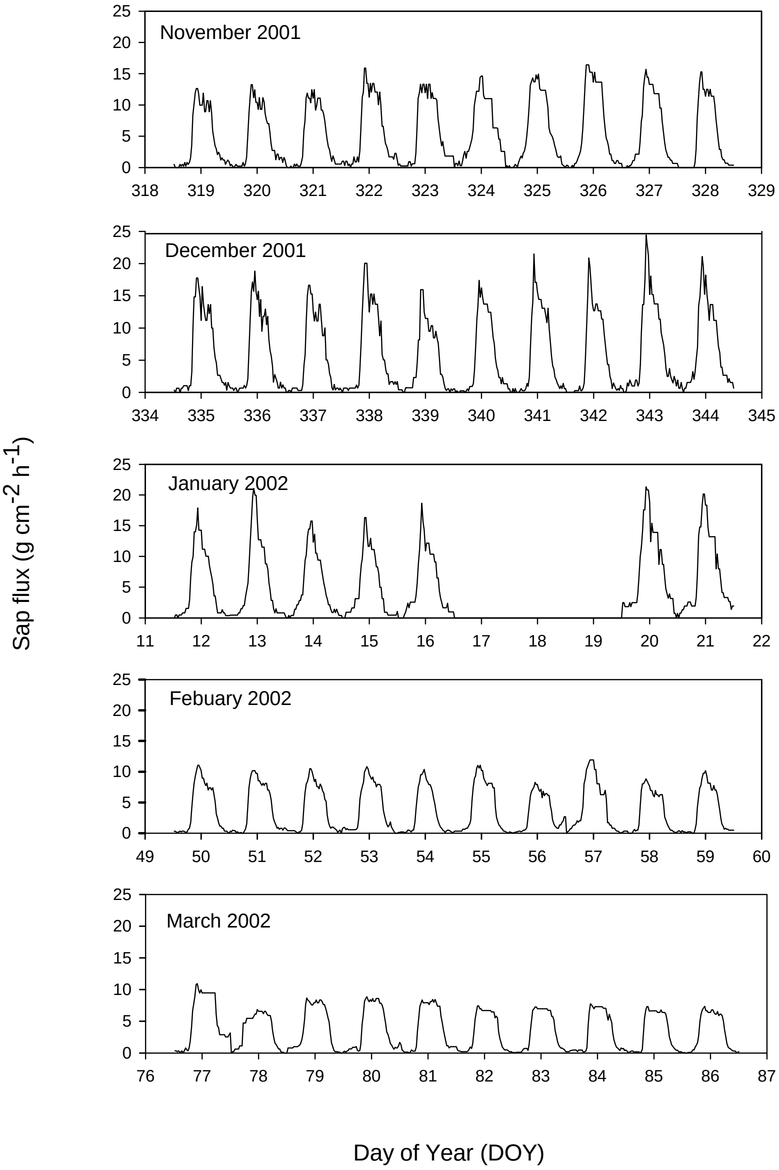

Figure 4. Mean sap flux density on sapwood area basis from November 2001 to March 2002 showing average of 47 days measurements during the drying period.

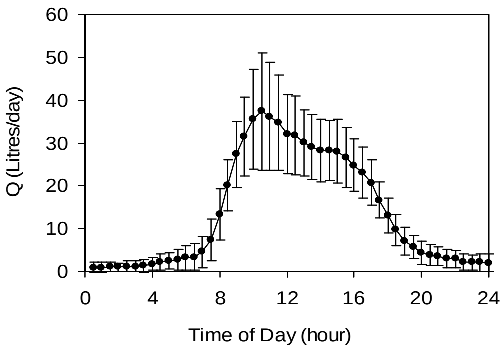

Figure 5. Overall mean diurnal water use (litres day^{-1}) pattern of *Anacardium occidentale L* over a typical dry season (vertical bars represent ± standard deviation).

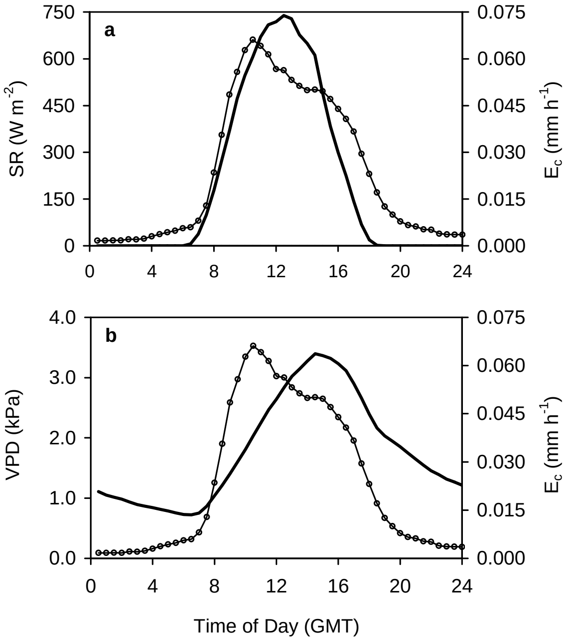

Figure 6. Mean diurnal pattern of tree water use (line with circle), and solar radiation, and (b) vapour pressure deficit.

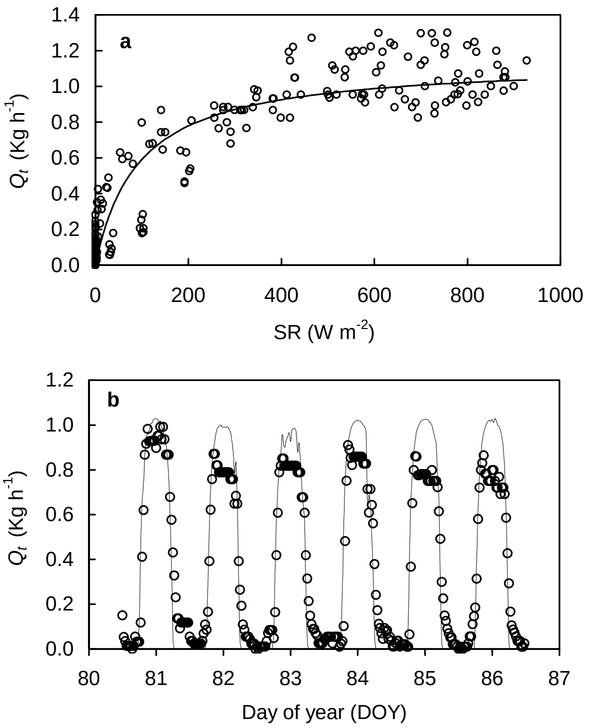

Figure 7. The dependence of sap flow on solar radiation (a) curve fitting result from Eq. 4, and (b) example of the measured (circle) and fitted (line) sap flow in half-hourly resolution.

Canopy conductance

Canopy conductance (g_c), derived by inversion of Penman-Monteith equation and aerodynamic conductance (g_a), showed considerable diurnal variations. The diurnal course of the computed g_c averaged over the measurement period is shown in Figure 8a. It increased slowly from mid-night and rapidly between 700 and 900 hour, at which time maximum g_c occurred and decreased to the lowest value after 2000 hour. Estimated g_c, ranged from 0.1 to 2.2 mm s^{-1} from mid-night to 900 hour. Aerodynamic conductance (g_a) also rises to its peak between 900 and 1000 hour and was always of higher magnitude as compared to g_c (Figure 8b). The order of magnitude ranged from 21 to 49 times, during the daytime.

Tree water use declined as g_c decreased. Readily available soil water led to higher tree conductance and transpiration while water deficit led to lower conductance and transpiration despite the prevailing higher atmospheric demand. Regardless of soil water availability, plant resistance may also limit water uptake under high evaporative conditions (Margolis and Ryan, 1997). When this occurs, water uptake becomes uncoupled from the course of atmospheric water demand leading to higher canopy resistance (Cienciala et al., 2000). According to Machado and Tyree (1994), plant resistance can also be affected by embolism of conductive tissues particularly during drought. We observed reduction in

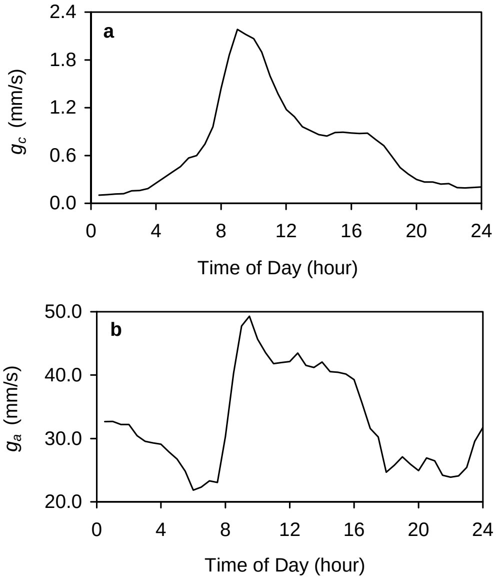

Figure 8. Daily course of (a) derived tree canopy conductance (g_c), and (b) estimated aerodynamics conductance (g_a).

transpiration and increasing plant resistance under high evaporative demand and high moisture deficit for *A. occidentale*. The relative importance of stomatal in regulating water use and aerodynamic coupling between tree canopy and the atmosphere could be estimated by decoupling (Ω) parameter (Javis and McNautghon, 1986). Omega, Ω, was not estimated here because humidity was not measured within the tree canopy. However, the result of a simple parabolic model in equation (4), where solar radiation was found to explain about 90 % of the variations in tree water use, may suggest that *A. occidental* canopy is not well coupled to the atmosphere.

Table 1. Mean comparison of canopy transpiration during the measurement period.

[#]Month (I)	Month (J)	Md (I-J)	Sig. level	Remark
1	2	-0.061	0.108	ns
1	3	-0.067	0.112	ns
1	4	0.191	<0.001	*
1	5	0.205	<0.001	*
2	3	-0.005	0.896	ns
2	4	0.252	<0.001	*
2	5	0.267	<0.001	*
3	4	0.257	<0.001	*
3	5	0.272	<0.001	*
4	5	0.015	0.692	ns

[#]I and J are compared months (1-November, 2-December, 3-January, 4-February, and 5-March), Md is mean difference.

Conclusions

Cashew is a drought-tolerant tree species currently being cultivated extensively across the West African savannah zones. Sap flow was highly related to the tree sapwood and generally decreased over the drying period. Water use during the phenological stage of flowering and fruit development was relatively higher during this dry period. A simple model relating a parabolic response of tree sap flow to solar radiation adequately captured the diurnal course of water use by cashew trees. The canopy scale processes showed that tree crown conductance slightly decreased over the dry season in response to declining soil moisture and increasing atmospheric demand. Solar radiation has a dominant influence on transpiration processes as compared to other climatic variables. The data is expected to be of value to land surface modeling especially over Volta southern sub-basin in West Africa.

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