Water Flux in a Cashew Orchard during a Wet-to-Dry Transition Period: Analysis of Sap Flow and Eddy Correlation Measurements

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ABSTRACT: Information regarding biosphere–atmosphere interactions is important in the study of a hydrological cycle. To this purpose, xylem sap flow (S_F) using the Granier system and evapotranspiration (E_T) using the eddy

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correlation method were measured during a “wet-to-dry” transition period in a young cashew (*Anacardium occidentale* L.) plantation. Estimates of half-hourly tree transpiration made from stem sap flow measurements and above-canopy eddy correlation measurements of water vapor flux were compared for a period of 22 days of complete records. Cross-correlation analysis was used to estimate the time lags (τ) between the time courses of S_F and E_T, and between S_F and E_T with solar radiation (R_S) and vapor pressure deficit (D). Applying a simple functional technique, values of $\tau = 43$ min (November), $\tau = 46$ min (December), and $\tau = 75$ min (January) with an overall $\tau = 53$ min (using all data) between the time courses of E_T and S_F were estimated. A positive lag indicates that S_F lags behind E_T. However, both E_T and S_F were more dependent on R_S ($r^2 > 0.81$) than on D, whereas S_F was more related to D ($r^2 = 0.60$) compared to E_T ($r^2 = 0.38$). An insignificant ($p > 0.05$) decrease in daily values of both E_T and S_F over the 22 days of concurrent measurements were observed. Daytime average E_T ranged from 2.01 to 3.17 mm day^{-1} with a mean of 2.7 mm day^{-1}, whereas values of S_F ranged from 0.55 to 0.72 mm day^{-1} with a mean of 0.65 mm day^{-1}. Tree transpiration accounted for about 25% of the evapotranspiration from the orchard. This result may be of help in correctly predicting the diurnal behavior of transpiration from sap flow measurements.

KEYWORDS: Biosphere–atmosphere; Time lag; Evaporative fraction

1. Introduction

Pertinent to our understanding of regional and global change in the hydrological cycle is the knowledge of biosphere–atmosphere interactions that includes the effects of climate on ecosystem functions and the potential feedbacks of the land surface to the physical climate system. Studying these interactions requires a nested experimental design whereby measurements of fluxes are taken using a variety of methods at different time and space scales (Margolis and Ryan 1997). Forest and woodland ecosystems often include an understory of grasses, forbs, shrubs, or smaller woody plants (Scott et al. 2003) that may make significant contributions to the total ecosystem flux depending on stand structure. Generally, in closely spaced stands, trees play a dominant role in evapotranspiration, whereas in stands with widely spaced trees, evaporation from understory vegetation, litter, and soil are major components of the total ecosystem water loss (Eastham et al. 1988; Kelliher et al. 1990; Scott et al. 2003).

Furthermore, information on temporal patterns and dynamics of water fluxes from soil to canopy is relatively scarce in moist tropical forest, but may be of importance to climate models (Godstein et al. 1998; Phillips et al. 1999). It has been observed that the diurnal trend of sap flow tends to lag behind evapotranspiration due to the hydraulic capacitance of the plant, and the nonzero response time required in getting the sap flowing once an evaporative demand has been applied to the leaves. To understand these temporal dynamics, there is a critical need to measure time lags (τ) in water movement through plants for the purpose of estimating canopy transpiration and conductance from xylem sap flow data (Diawara et al. 1991; Granier and Loustau 1994; Phillips et al. 1997). Time lag for water transport between stems and canopies can be estimated based on lags between stem uptake and canopy eddy flux measurements (Granier and Loustau 1994; Phillips et al. 1997). Although some studies have neglected the use of lag times (Köstner et al. 1992; Cienciala et al. 2000), errors introduced to the instantaneous estimate of canopy transpiration could be up to 30% on a stand level if lags were disregarded (Phillips et al. 1999).

Within the framework of the ongoing GLOWA-Volta project [Global Change in the Hydrological Cycle (GLOWA); van de Giesen et al. 2002], a research project designed to study "sustainable water use under changing land use, rainfall reliability, and water demands in the Volta basin" (West Africa), sap flow, eddy correlation, and/or large-aperture scintillometry systems (available online at www.glowa-volta.de) were used concurrently to measure field level fluxes. The results reported here cover measurements taken during a dry-down (transition) period between November 2002 and January 2003 near Ejura in the southern part of the Volta basin. The objectives of this study were 1) to examine the temporal patterns between xylem sap flow and eddy water flux and their interaction with the atmospheric forcing with a view to determine their respective lags, and 2) to estimate the relative contributions of trees and understory components of evapotranspiration in this ecosystem.

2. Materials and methods

2.1. Study site

The study was conducted in the small village called Samari Kura (Kotokosu watershed), 15 km east of Ejura, Ghana. The experimental plot site was located within a young, widely spaced cashew orchard (≈90 ha; 07°20′18″N latitude, 01°16′37″W longitude, elevation 200 m). This location lies in the forest–savannah transition zone of Ghana. Tree density was estimated at 175 trees per hectare with projected crown cover of 30%, which translated to a gap fraction of about 0.7. A range of annual crops such as maize (*zea mays*) and cowpea (*Vigna unguiculata*) were planted within rows, and a mosaic of weeds and grasses forms the understory. The plantation is maintained in a form that tends to agroforestry in that the orchard owner gives out portions of the plantation to the landless farmers who farm on the plot and as a result help keep the fields from becoming too weedy. During the rainy season, a number of small ponds are scattered within the watershed and the flood plains are usually swampy with a little stream (Kotokosu) draining the entire watershed. Rice is cultivated along the valleys and on the flood plains. The rainfall is bimodal with a wet season between April and October. Total rainfall in 2002 was 1380 mm. The amount of rainfall recorded during the observation period was 70.5 mm (Figure 1).

2.2. Sap flow measurements

Sap flow was measured within a 2500 m^2 plot (adjacent to the eddy correlation site) using the temperature difference method of Granier (Granier 1987). Two cylindrical probes, about 2 mm in diameter, were implanted in the sapwood of the tree trunks with previously installed aluminum tubes, separated vertically by 12 cm

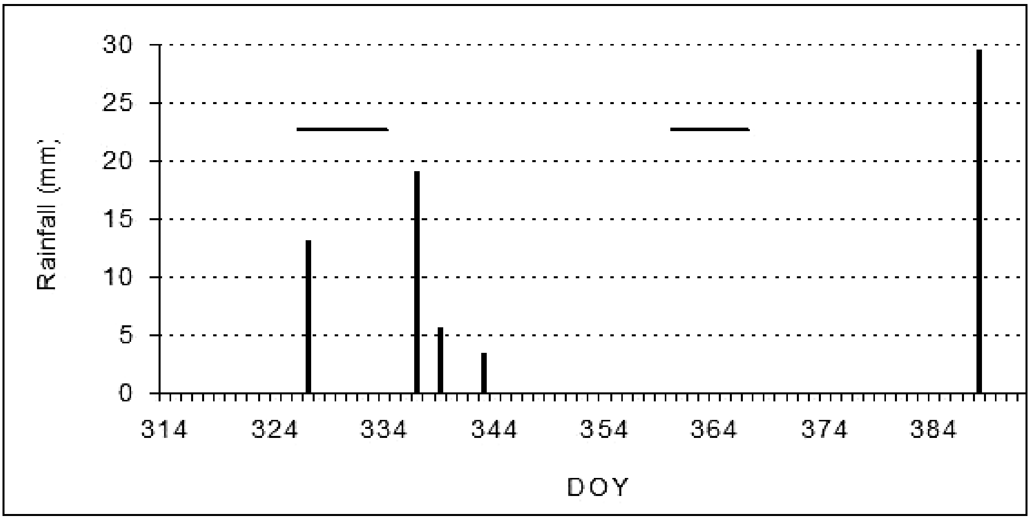

Figure 1. Observed rainfall during the 79 days of eddy correlation measurements. DOY 366 = 01 Jan 2003 and the horizontal bars show the period of sap flow measurements.

at chest height (1.3 m). The probes were installed on the north side of the tree to minimize direct heating from sunshine and then shielded with aluminum foil against rainfall. The downstream probe was continuously heated with a constant power source (UPGmbH, Munich, Germany), whereas the unheated upstream probe served as a temperature reference. The dissipation of heat from the upstream heated needle will increase with increasing sap flow rate. During conditions of zero sap flow, such as nighttime, the temperature difference between the lower and the upper probes represents the steady-state temperature difference caused by the dissipation of heat into nontransporting sapwood. Whole-tree sap flux density was computed with the empirical relationship supplied by the manufacturer (UPGmbH 2001) as

$$S_f = 0.714[(\mathrm{TD}_m/\mathrm{TD}) - 1]^{1.231}, \tag{1}$$

where S_f (mL cm^{-2} min^{-1}) is the sap flow density, TD is the temperature difference between the two probes, and TD_m is the baseline (maximum) temperature difference for the dataset of the day.

Sap flow was measured on three cashew trees that were selected to represent the diameter distribution of the plot. The trees in the entire orchard plantation are even-aged and of relatively uniform size, with each tree crown fully exposed to the sun. A linear relationship between sapwood area (SA) and tree circumference (CT) at chest height (1.3 m) was established (Figure 2) to estimate xylem area at the base of the trees. Weighted average sap flux density values from the plot (gauged trees) were scaled to transpiration (stand) on a unit ground area base by multiplying it with the total estimated sapwood area of all the trees in the plot. Similarly, crown transpiration was estimated using a total of an estimated canopy area cover of

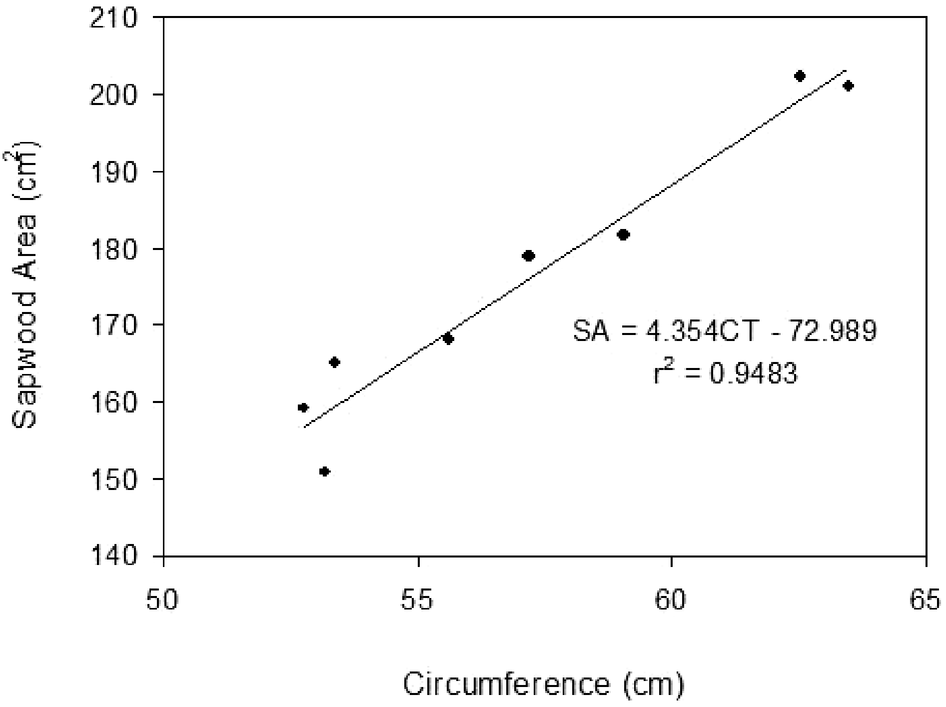

Figure 2. A relationship between sapwood area (SA) and tree circumference at chest height (CT).

individual trees (using Spiegel relaskop measurements of canopy girths) in the place of ground area cover in stand transpiration. Sap flow measurements were made between DOY 323–334, DOY 359–365, and DOY 1–3 2002/03. A total of 22 days of complete half-hourly averages of 30-s observations were used in this study. This period represent a significant dry-down as only one rainfall event was recorded during the measurement (Figure 1).

2.3. Eddy correlation measurements

An eddy correlation (EC) system was used to measure latent (LE) and sensible heat (*H*) fluxes over the orchard. This device was mounted at a height of 10 m, which was about 4.8 m above the mean tree height, from a tower installed in the middle of the plot. The three axis components of wind speed were measured with a 3D sonic anemometer (Gill Instruments Ltd., United Kingdom) and water vapor flux was measured with a krypton hygrometer (model KH_2O, Campbell Scientific, United Kingdom). A detailed description of the set up and operation of the device is given by Elbers (Elbers 2002). Half-hourly average EC data were analyzed and made available by Burose et al. (Burose et al. 2004, manuscript submitted to *Bound.-Layer Meteor.*). Eddy correlation measurements covered the period between 9 November 2002 and 28 January 2003. A total of 79 days of reliable data were available over this drying transition period.

2.4. Soil moisture and weather measurements

Soil water content (θ) was routinely measured during the 22 days of sap flow observations. A profile probe type PR1 (Delta-T Devices, Cambridge, United Kingdom) was used in one access tube located on bare soil within the 2500 m^2 plot. Four sensors were arranged at 10-cm-depth intervals down to 40 cm, whereas one was placed at 60 cm and the last one at 100 cm. A conversion formula for mineral soils (supplied by the manufacturer) was used to obtain volumetric θ from the millivolts data recorded. The average profile soil moisture was estimated over the six sensors in the column. Weather variables, such as incoming solar radiation, net radiation, air temperature, wind speed and direction, relative humidity, and rainfall, were sampled at 10 s and recorded as 10-min averages with an automatic weather station installed about 800 m away from the eddy correlation plot.

2.5. Time lag estimation

The dynamic responses of whole tree sap flow (S_F) and evapotranspiration (E_T) to environmental driving forces, solar radiation (R_S), and vapor pressure deficit (D), were assessed using a cross-correlation analysis. Time lags (τ) were estimated for 1) tree-canopy pairs, that is, S_F and E_T; and 2) stem and canopy individually with respect to both R_S and D. A range of time lags were introduced for each pair of time series, and the corresponding range of correlation coefficient (r) was obtained by use of the cross-correlation function (ccf) given as

$$r = \frac{\mathrm{cov}[X(t), Y(t+\tau)]}{\sigma_x \sigma_y}, \tag{2}$$

that is, the covariance of X and Y time series variables divided by the product of their standard deviations, σ_x and σ_y, respectively. The correlation between X and Y is r, t is time, and τ is a lag introduced between X and Y.

The lag that corresponds to maximum r is retained as the time lag for that pair. This procedure is commonly used to determine the lag between time series pairs (Phillips et al. 1997; Phillips et al. 1999; Post and Jones 2001; Bond et al. 2002). Its accuracy is mainly affected by the periodicity or the averaging period for the measurements. For example, the lag for a time series pair with 20-min time steps will be to the nearest 20 min, and the one for 5 min will also be to the nearest 5 min. Therefore, to determine the optimal time lag (or locating the actual maximum correlation), we fitted a quadratic model (the most successful equation with coefficient of determination, $r^2 > 0.99$) between correlation (r) and τ:

$$r = a\tau^2 + b\tau + c, \tag{3}$$

where a, b, and c are the constant coefficients of the function and $a \neq 0$. The lag corresponding to the maximum value for r was found by

$$\frac{dr}{d\tau} = 2a\tau + b = 0 \quad \text{or} \quad \tau = \frac{-b}{2a}. \tag{4}$$

This analysis was done for 12 days of available data in November (DOY 323–334), 7 days in December (DOY 359–365), and 3 days in January (DOY 1–3).

3. Results

3.1. Xylem flow–eddy flux diurnal relations

In Equation (2) X corresponds to evapotranspiration (E_T) and Y corresponds to sap flow (S_F). Cross correlations at different time lags (τ) between E_T and S_F are presented in the form of correlograms in Figure 3. Positive lag means that S_F lags behind E_T. The patterns of the correlograms for November and December look similar. The observed correlation ranged from 0.68 to 0.92 in November and ranged from 0.64 to 0.91 in December. The maximum r being at $\tau = 30$ min for both months. The time lag for the period in January was quite different, with τ between 60 and 90 min, and the maximum correlation at $\tau = 60$ min. Using all the data in one single cross-correlation analysis yielded a slightly different picture. The time lag was between 30 and 60 min, with the maximum $r = 0.90$ at $\tau = 60$ min. The τ values presented are obviously to the nearest periodicity or the time series–averaging period, which is just half-hourly in this study. The correlation coefficients near the maximum (Figure 3) are transformed with the Fisher Z-transformation approach and the Z test was carried out to test whether the set of correlations near maximum is significantly different. For November, December,

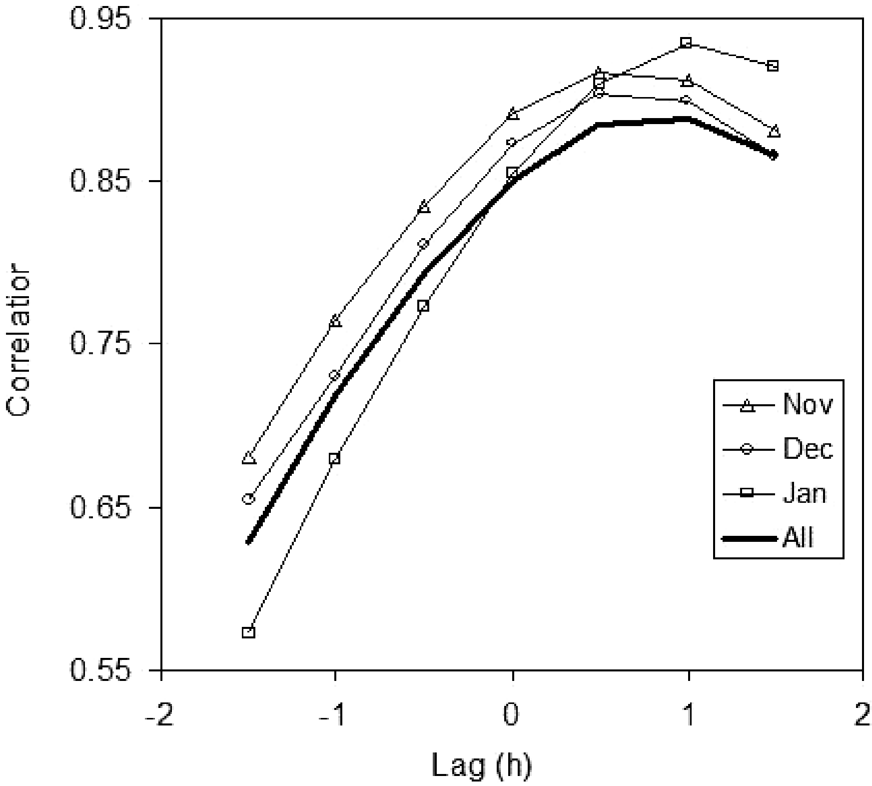

Figure 3. Cross correlation between evapotranspiration and stem sap flow (Equation (2)). Maximum r for each curve corresponds to the time lag for each period analyzed.

and combined data, correlations at lags from +0.5 to 1 h were not significantly different, but for January, all the correlations near maximum are significantly different. Hence, using the simple analysis presented in Equations (3) and (4), an optimal r leading to a more exact τ value was determined. The r^2 for Equation (3) was very high for each of the periods considered ($r^2 > 0.991$). The lag was estimated as 43 min in November, 46 min in December, and increased to 75 min in January. For the combined data, $\tau = 53$ min.

A comparison between measured tree transpiration and evapotranspiration showing diurnal patterns is presented in Figure 4 (stand transpiration is per unit of ground area, whereas crown transpiration is per unit of crown area). The diurnal average for each corresponding measurement period was used. Generally, the temporal evolution of transpiration is smoother than the water flux measured by the eddy correlation system. It should be noted that xylem flow lagged behind evapotranspiration even with a time lag of 30 min taken into account in plotting Figure 4. This 30-min time lag was included by plotting $S_F\ (t+0.5)$ at $S_F\ (t)$, where $t = 1$ h. Stem flow started later and reached a maximum earlier than evapotranspiration. Eddy correlation measurement indicated some negative values during the night and the early morning times, which are not consistent with the near-zero value measured with the sap flow method. In addition, evapotranspiration by eddy correlation was more perturbed by transient daytime atmospheric conditions than sap flow (Phillips et al. 1997). The patterns of above-canopy water flux were quite similar for the three observation periods but transpiration changed slightly. In November (DOY 323–334), tree transpiration reached a maximum in the midmorning and stayed almost constant for the entire afternoon before decreasing in the evening, whereas in December (DOY 359–365) and January (DOY 1–3), tree transpiration reached a maximum in the midmorning, decreased slowly during the afternoon, and showed a sigmoid decrease during the late afternoon to evening. To estimate the extent to which the variation of eddy water flux and transpiration are correlated, we regressed tree transpiration (stand and crown) with evapotranspiration. The value of r^2 indicated that there is up to 70% agreement in the diurnal patterns of sap flow and the eddy flux.

3.2. Water flux–climatic forcing temporal dynamics

The diurnal evolution of sap flow (S_F), eddy flux (E_T) expressed as latent energy (LE), solar radiation (R_S), and vapor pressure deficit (D) averaged over the measurement period (22 days) are shown in Figure 5. It can be seen that 1) both eddy water flux and sap flow are well correlated to radiation with eddy flux showing a better coupling, and 2) the vapor pressure deficit lagged behind both eddy flux and sap flow. Correlations over a range of time lags (–180 to +180 min) between climatic parameters and water fluxes are presented in Table 1. For R_s versus S_F, r ranges from 0.40 to 0.92; for R_s versus E_T, r varies between 0.40 and 0.93; whereas r ranges from 0.23 to 0.81 and –0.06 to 0.79 for D versus S_F and D versus E_T, respectively. Positive lags indicate that the second variable of the listed pairs lags behind the first variable. A test of the equality of correlations was performed as described earlier and different letters attached to the respective correlation value relevant to each pair signify differences between correlations. The

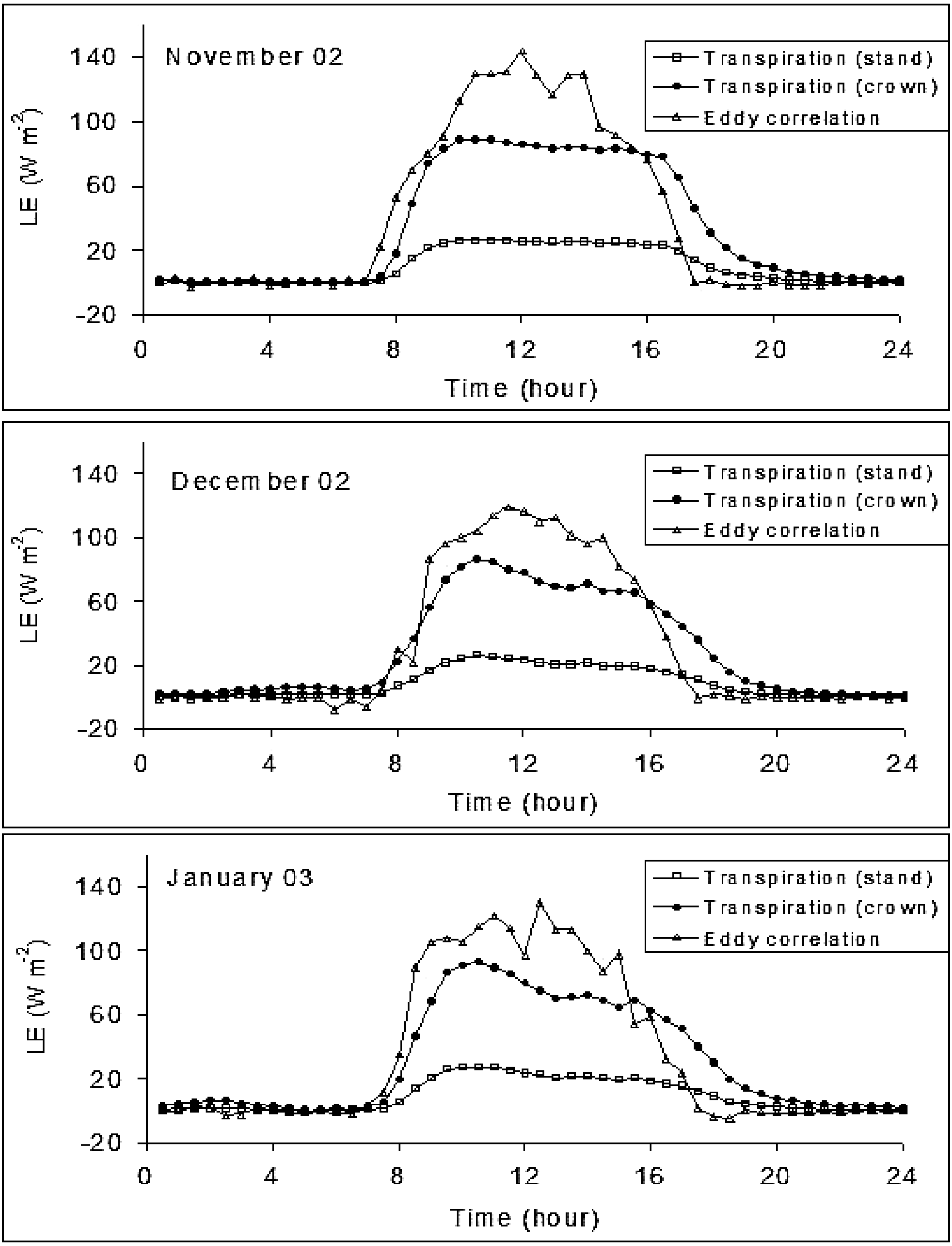

Figure 4. Mean diurnal course of latent heat fluxes as measured by eddy correlation and sap flow measurement systems. Transpiration was computed per unit of crown area and per unit of ground area (a lag of 30 min was included in the transpiration).

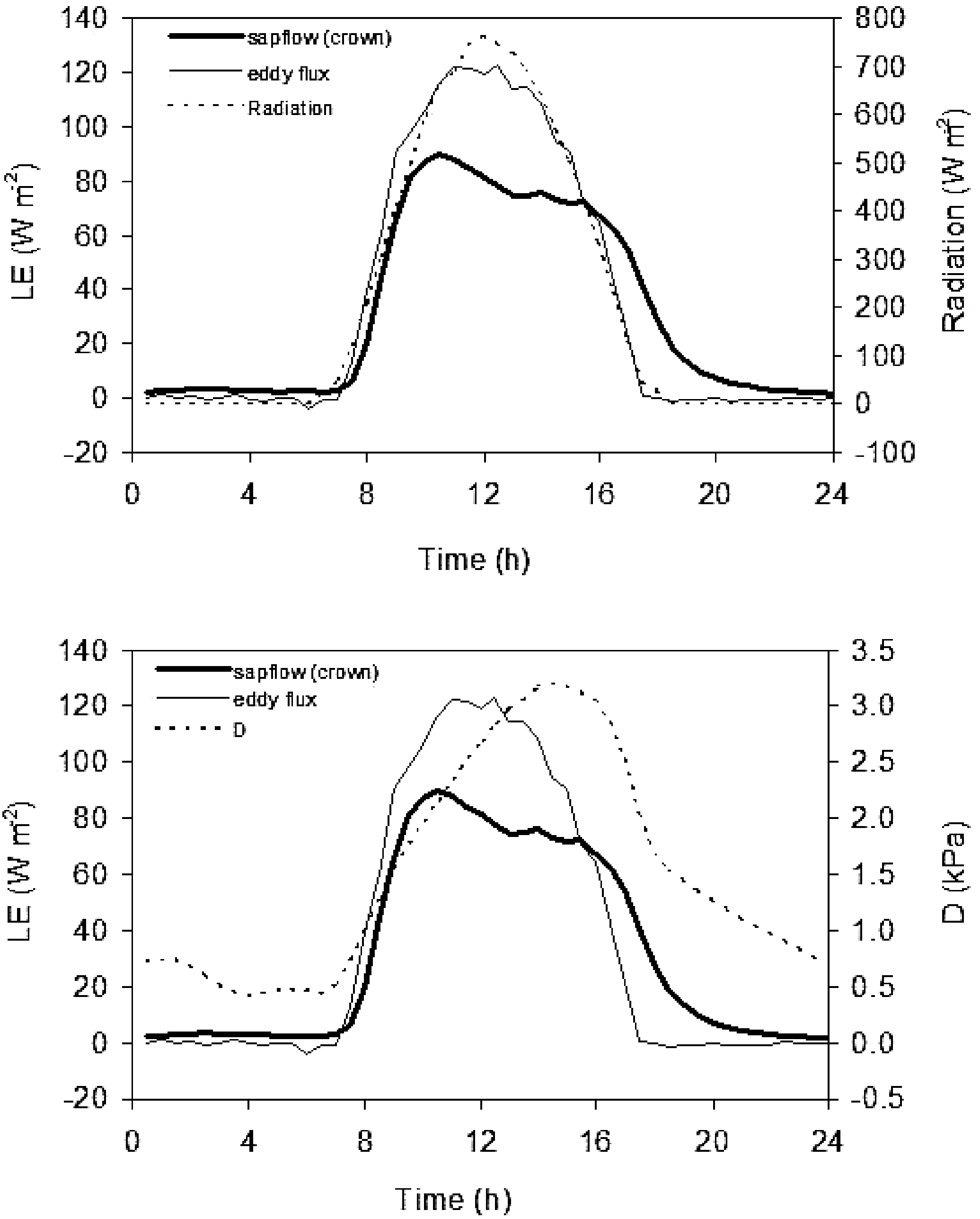

Figure 5. Temporal patterns of water fluxes (LE) in relation to (a) solar radiation (R_S) and (b) vapor pressure (D) with time lag of 30 min (avg of 22 days).

time lags between water fluxes (E_T and S_F) and R_S or D were thereafter estimated according to Equations (3) and (4). Combining all the data ($n = 1056$), R_S lagged E_T by 25 min ($r = 0.92$), but E_T led D by up to 133 min ($r = 0.78$). Similarly, S_F lagged R_S with a slightly longer duration ($\tau = 33$ min; $r = 0.92$), whereas D lagged S_F by about 66 min ($r = 0.81$).

Table 1. Correlations obtained between radiation (R_s) and vapor pressure deficit (D) with evapotranspiration (E_T) or sap flow (S_F) in pairs using cross-correlation analysis at different lag times. Positive lags indicate that the second variable of the listed pairs lags behind the first variable.

	Correlation coefficient (r)			
Time lag (min)	R_s vs S_F	R_s vs E_T	D vs S_F	D vs E_T
−180	0.40	0.59	0.70	0.77a
−150	0.51	0.70	0.75	0.79a
−120	0.62	0.78	0.78b	0.78a
−90	0.72	0.86c	0.80a	0.77a
−60	0.80	0.90b	0.81a	0.73b
−30	0.86c	0.93a	0.80a	0.67
0	0.90b	0.91b	0.78b	0.59
30	0.92a	0.87c	0.73b	0.49
60	0.91b	0.80	0.65	0.38
90	0.87c	0.72	0.56	0.27
120	0.82	0.62	0.46	0.16
150	0.74	0.51	0.35	0.05
180	0.66	0.40	0.23	−0.06
r max*	0.92 (33)	0.92 (−25)	0.81 (−66)	0.79 (−133)

* Estimated from Equations (3) and (4). Estimated lag (min) is in parentheses. Differences in r near maximum are signified by different letters attached to r values along each column, while correlations with the same letter attached are not significantly different from one another.

3.3. Daily estimates of sap flow and eddy fluxes

Daily estimates of tree transpiration and evapotranspiration were computed as sums between the hours of 0700 and 1600 UTC. This was to avoid the nighttime and early morning (negative values) evaporation from the eddy correlation measurements. Figure 6 shows the daily pattern of the fluxes over the 22 days of concurrent measurements (DOY: 323–334, 359–365, and 1–3). The data are shown in two plots [(a) and (b)] to avoid data compression due to data gap. The values for eddy flux ranged from 2.01 to 3.17 mm day^{-1} with a mean value of 2.7 mm day^{-1} and a coefficient of variation of 12%. Generally, there was a slight decrease in daily values during this drying transition period. Similarly, the observed stand transpiration decreased slightly ($p > 0.05$) over the period. The value ranged from 0.55 to 0.72 mm day^{-1} with a mean of 0.65 mm day^{-1} [coefficient of variation (CV) = 8%]. On average, the contribution from trees was estimated at about 25% of the evapotranspiration.

To assess the general pattern of evapotranspiration over the wet-to-dry transition period, the evaporative fraction (EF) as the ratio of latent heat (LE, W m^{-2}) to available energy was computed as

$$\mathrm{EF} = \frac{\mathrm{LE}}{\mathrm{LE} + H}, \tag{5}$$

where H (W m^{-2}) is the sensible heat flux. The daily time series (averaged between 0700 and 1600 UTC) for LE and EF for the 79 days between DOY 314 and DOY 27 (2002/03) are shown in Figure 7. Both LE and EF decreased

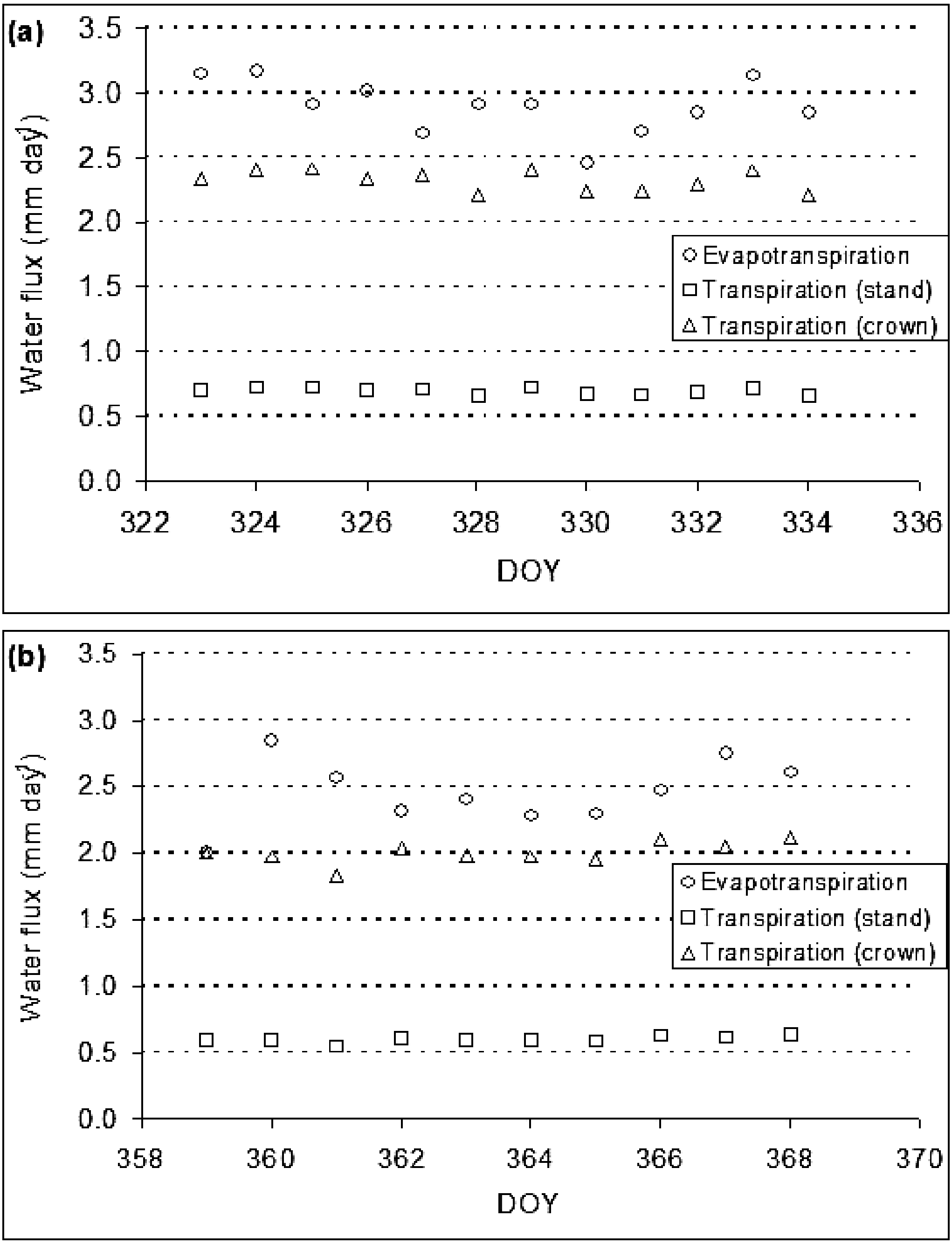

Figure 6. Daily values of tree transpiration (crown and stand) and evapotranspiration (averaged between 0700 and 1600 UTC) for (a) DOY 323–334 and (b) DOY 359–365, 01–03). DOY 366 = 01 Jan 2003.

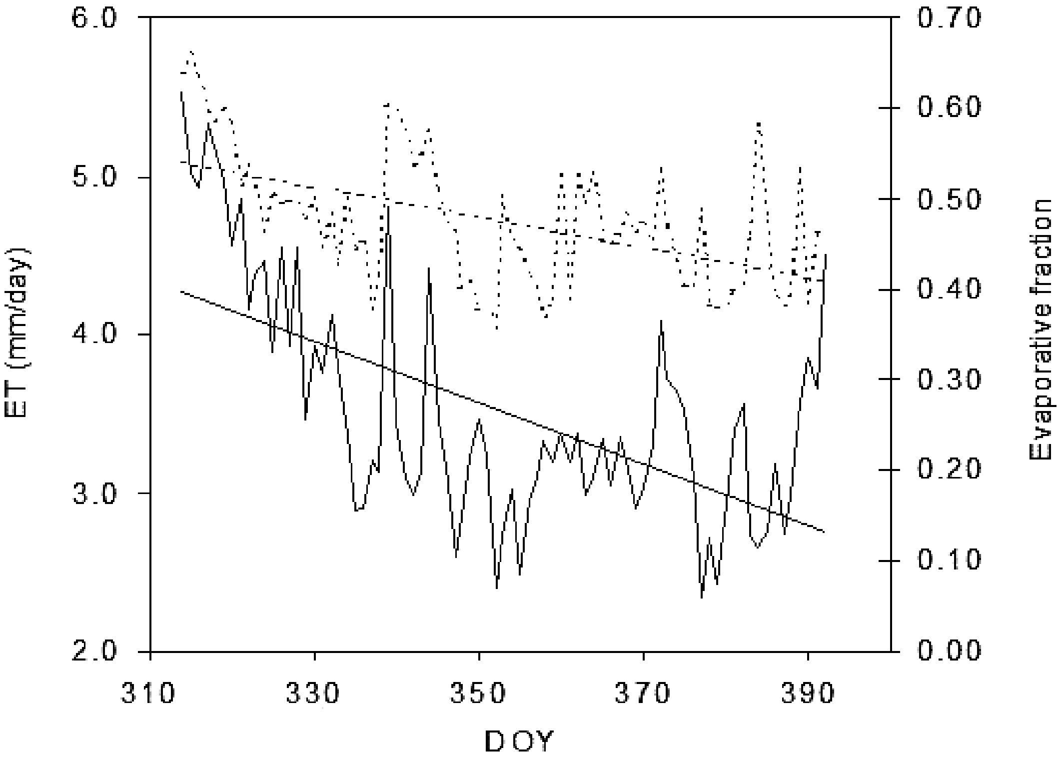

Figure 7. Evapotranspiration (solid line) and evaporative fraction (dashed line) observed for 79 days during the wet-to-dry transition period. DOY 366 = 01 Jan 2003.

gradually. Evapotranspiration varied from 2.33 to 5.52 mm day^{-1} with a mean of 3.52 mm day^{-1}, and the average evaporative fraction was 0.48 and ranged between 0.66 (days following end of rainy season) to 0.36 (at the end of transition period).

4. Discussion

Considering the fact that there was a total rainfall of about 13 mm on only 1 (DOY 327) out of the 22 days of concurrent measurements, and that a total of 28 mm was observed between DOY 337 and 343, the entire measurement period could be referred to as a "drying out" or transition period. The estimated time lag between E_T and S_F increased gradually as the drying-out progresses. This result was similar to previous studies that reported a nonconstant time lag in maritime pine (Loustau et al. 1996) and jack pine (Saugier et al. 1997). Although the interpretation of the time lag is complex, changes in water storage along the stem and leaves above the gauging sensors are thought to be partly responsible for it (Saugier et al. 1997; Phillips et al. 1999). Phillips et al. (Phillips et al. 1997) observed weak correlations over a broad range of lags and attributed this to fluctuations in the vertical vapor fluxes. However, in the results presented here, correlation is generally high possibly because the averaging time (30 min) used is higher than the one used in their study. Furthermore, the narrower range of τ for which correlations are statistically similar in this result may be attributed to the same reason. During this period of 22 days, we observed an insignificant decrease in transpiration, which suggests that the increase in τ may be a result of lower transpiration rates leading to more time needed to replenish the water stored above the gauging sensors. Furthermore, since this period is mainly used by *A. ocidentale* for flowering and fruiting, changes in water uptake, storage, and release may be an adaptation strategy for the tree to cope with the impending water deficit.

The observed behavior of stem flow and eddy flux in relation to radiation and vapor pressure deficit slightly differs. Whereas E_T quickly responds to radiation and follows it throughout the day (Figure 5), S_F responds a bit later and follows R_S up to late afternoon (1600 LT), after which there is indirect evidence that D becomes influential judging from the similarity in the curves during the afternoon. Radiation was the main driver for evaporation both from the trees and the understory. The fast responses of water fluxes to R_S coupled with higher r may indicate their aerodynamic decoupling from the atmosphere. There is a higher time lag (133 min) between E_T and D than compared to S_F (66 min). This observation may depend on the D regime sampled here and possible differences may occur under a very dry climatic condition. The high divergent time lag between E_T and S_F (with D) stated above may be due to the undergrowth contribution to the evapotranspiration. Many studies have shown that such within-row grasses and understory are almost completely decoupled from vapor pressure deficit but highly related to the net radiation (Diawara et al. 1991; Scott et al. 2003). The statistically similar correlations near the maximum observed were similar to the result of Phillips et al. (Phillips et al. 1997). This was attributed to large fluctuations characterizing EC data and made these authors critical about the use of E_T and S_F data of 20-min resolution. One of the difficulties lies in getting the optimum correlation from this type of data. Therefore, the proposed functional technique in this study may be helpful in locating the actual r maximum. However, this method should be further tested especially over a range of averaging intervals commonly used in micrometeorological measurements.

The relative contribution of trees to the evapotranspiration is small compared to the undergrowth (grasses, crops, short shrubs, and bare soil) that covers about 70% of the plot and understory beneath the trees. The lower percentage of evapotranspiration contributed from the cashew trees may be partly due to low tree density (about 175 trees per hectare). Previous studies have shown that transpiration from trees can account for about 90% of the evapotranspiration from closely spaced stands (Kaufmann and Kelliher 1991), whereas in stands with widely spaced trees, evaporative loss from the understory vegetation, soil, and litter can become the major component, as observed in agroforestry systems (Eastham et al. 1988) and in young stands where the trees have been thinned and pruned (Kelliher et al. 1990). Furthermore, in two *Acacia mangium* plantations, where one stand had a density that was about double that of the other, Cienciala et al. (Cienciala et al. 2000) observed a large difference in their respective stand transpiration rates. Since evaporation contributed by different understory components was not directly measured, total understory contribution could be treated as the residual of evapotranspiration and tree transpiration estimates.

However, this understory evaporation quantity is uncertain due to uncertainties associated with, for example, scaling tree to stand transpiration (Granier et al. 1990; Cienciala et al. 2000) and errors inherent in evapotranspiration by eddy correlation (Twine et al. 2000; Brotzge and Crawford 2003).

Similar to Granier et al. (Granier et al. 1990), the between-tree variability of sap flux density was low, probably because the trees are young, even-aged, and of low stem density that allowed full crown exposure eliminating possible shadowing effects. Instrument error, surface heterogeneity, and the theoretical assumptions behind the eddy correlation method have been used to explain problems of energy budget closure (Brotzge and Crawford 2003). However, Burose et al. (Burose et al. 2004, manuscript submitted to *Bound.-Layer Meteor.*) have presented a detailed report on energy balance closure errors of the eddy correlation data used in this study, and they find an acceptable relative energy imbalance (about 20%) as compared to other similar studies. Another source of discrepancies in the value of eddy flux relative to sap flow is the possibility of advected moisture from nearby ponds, swamps, and the stream. These surfaces are within 250–450 m in a valley meandering around the experimental site and passing through the entire 90-ha plantation. A roughly estimated footprint analysis showed that average daytime fetch could vary from 200 to 600 m. Hence, there is a likelihood that vapor flux from these water bodies and rice fields may affect the magnitude of the evapotranspiration observed with the eddy correlation method.

Based on the estimated average evaporation fraction, less than 50% of the available energy was used in actual evapotranspiration during the wet-to-dry transition season studied. The observed decreases in evaporative fraction suggest that there is a slight change in biosphere–atmosphere interaction (increase in surface resistance) over the studied ecosystem during the transition from a rainy to a dry season. A high evaporative fraction translates to a lower boundary layer depth, whereas low evaporative fraction results in the development of deep, dry atmospheric boundary layer (Margolis and Ryan 1997).

5. Summary and conclusions

Temporal dynamics of water fluxes and relative contributions from stand components were examined in a young, widely spaced, cashew orchard in Ghana. Using cross correlation and a simple functional technique, time lags between tree xylem flow and evapotranspiration were estimated. Similarly, lags between both fluxes and atmospheric variables (incoming solar radiation and vapor pressure deficit) were determined. Water fluxes were highly related to solar radiation. Average daily evapotranspiration during this drying transition period gradually declined while the proportion of the total available energy consumed in evaporation was less than 50%. A decreasing trend in evaporative fraction from 0.66 to 0.36 was observed, suggesting a slight increase in surface resistance. Due to low stem density of the plantation, the contribution from the understory was indirectly estimated to be greater than 70% of the evapotranspiration. It is suggested that in the ongoing field campaign, the component of understory evapotranspiration should be directly measured so as to allow for a more accurate partitioning of evapotranspiration in this ecosystem.

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