EFFECT OF AVERAGING INTERVALS OF HYDROMETEOROLOGICAL VARIABLES ON THE DIURNAL TIME LAG ESTIMATION IN SAP FLOW DATA

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ABSTRACT

The effect of temporal averaging periods of hydrometeorological parameters on the estimation of time lag for water transport in young cashew trees was investigated for 10 days, in a cashew orchard in Ghana. Sap flow (S_f) was measured using Granier sensors and above canopy eddy flux (E_c) was measured using an eddy covariance system. Measured weather variables include solar radiation (R_s), air temperature (T_a), relative humidity (RH), and wind speed (U_2). Evaporative demand (E^*), a surrogate for canopy transpiration, was estimated from these meteorological variables. Cross-correlation analysis (CCA) and a simple resistance-capacitance model were used to estimate the time lags (τ) between the diurnal patterns of E_c and E^*, E_c and S_f, of E* and S_f as well as between R_s and other fluxes at 10 min, 20 min, and 30 min averaging intervals (AI), respectively. For E_c - S_f and the range of lags introduced, the CCA yields correlation coefficient (R) that vary from: 0.60-0.89 (AI=10min), 0.60-0.90 (AI=20min), and 0.62-0.94 (AI=30min), with each AI showing a different lag at maximum R. The most intensive AI shows that S_f lag E_c by 10 min whereas the time-series based on 20 min AI yielded a lag of 20 min while 30 min lag was observed for time-series based on AI of 30 min. The results of the simple resistance-capacitance model showed that time lag in this young orchard was generally lower than 10 min. Lags between E_c - S_f pairs showed a decreasing order, from 6.4 min at AI =10 min to about 2 min at AI =30 min. E^* was found to lag E_c by about 3.1 min, 2.5 min and 2.1 min, respectively with increasing averaging interval. This result showed that hydrometeorological variables should be recorded at appropriate averaging intervals so as to obtain good accuracy in the estimation of time lag, which, in turns, is needed in converting sap flow data to diurnal transpiration values.

KEYWORDS: Temporal averaging intervals; time lag; hydrometeorological variables

List of Symbols and Abbreviations

Symbol	Meaning [unit]
AI	averaging intervals [min]
CCA	cross-correlation analysis [-]
DOY	day of year [-]
DSS	decision support system [-]
E^*	evaporative demand [mm day^{-1}]
E_c	above canopy eddy flux [-]
R	correlation coefficient [-]
RH	relative humidity [%]
R_s	solar radiation [w m^{-2}]
S_f	sap flow density [g cm^{-2} h^{-1}]
T_a	air temperature [°C]
τ	time lag [min]
U_2	wind speed [m s^{-1}]
Z	Test statistic [-]

1. INTRODUCTION

It has been observed that sap flow tends to lag behind canopy transpiration due to the hydraulic resistance/capacitance of the plant, and the non-zero response time of sap flow initiation once evaporative demand has been applied to the leaves (Hunt et al., 1991; Phillips et al., 1997). This is because the daily onset of transpiration causes water to be withdrawn from internal storage compartments in the trees leading to lags between changes in canopy transpiration and stem sap flow at the base of the tree (Meinzer et al., 2004). Hence the use of xylem sap flow data to estimate tree transpiration and canopy stomatal conductance critically depends on knowledge of the time lag between transpiration and the sap flow (Diawara et al., 1991; Hunt et al., 1991). However, time lags are not always known a priori, hence recent studies have shown the need to measure time lags (τ) in water movement through plants for the purpose of estimating canopy transpiration and conductance from sap flow data and for improved understanding of temporal dynamics in biosphere-atmosphere interactions (Granier and Loustau, 1994; Phillips et al., 1999). Although eddy fluxes are characterized by large fluctuations that make comparisons with sap flow data difficult (Diawara et al., 1991; Loustau et al., 1996), the time lag between sap flow and canopy can be estimated (Granier and Loustau 1994; Saugier et al., 1997). However, others have estimated time lag based on time-series pairs such as stem–branch fluxes (Goldstein et al., 1998; Ewers and Oren, 2000; Meinzer et al., 2004), stem flow-simulated transpiration (Phillips et al., 1997) or simulated sap flow-transpiration (Peramaki et al., 2001).

In a related study, Hupet and Vanclooster (2001) investigated the effect of sampling frequency of meteorological variables on the estimation of the reference evaporation. Their result clearly showed that inappropriate temporal sampling caused non-negligible errors in the estimated reference evaporation. The objective of this study was to determine the possible effects of averaging intervals (AI) of hydrometeorological variables (xylem flux, eddy vapour flux, evaporative demand, and solar radiation) on the estimation of lag time between stem-canopy fluxes and between solar radiation-stem or canopy fluxes time-series pairs.

The data presented are part of the on-going GLOWA Volta project (www.glowa-volta.de), a research project designed to study sustainable water use under changing land use, rainfall reliability, and water demands in the Volta basin (West Africa) aiming at producing a scientifically sound decision support system (DSS) for the sustainable use of water in the basin (van de Giesen et al., 2002). Because of the different inputs required for the DSS, several hydrometeorological measurements were made during an intensive observation period between November 2002 and January 2003 at Ejura, the southernmost of the selected experimental watersheds for this project. Eddy covariance data between DOY 359 and DOY 03 (2002/2003) were used for this study. Detail studies on the relative energy imbalance and closure errors with the EC system used in this study have been discussed elsewhere (Schuttemeyer, 2005). Generally, the observed closure error for this 10-day period was within the acceptable range (<10 %).

2. MATERIALS AND METHODS

2.1 Experimental Site

The experimental site is located in Kotokosu watershed, 15 km east of Ejura, Ghana (latitude 07° 20′ N, longitude 01° 16′ W, elevation ≈ 200 m). This location lies in the forest-savannah transition zone of Ghana, dominantly influenced by the tropical maritime air mass. The climate is classified as tropical monsoon. The rainfall is bimodal with a wet season between April and October. Total rainfall in 2002 was about 1400 mm and the average between 1973 and 1992 was 1264 mm. Average air temperature for the same period was 26.6 °C (Adu and Mensah-Ansah, 1995; Agyare, 2004). The geological formation consists of Voltaian sandstone, and is characterised by gently dipping or flat-bedded sandstones, shales, and mudstones that are easily eroded. This has resulted in an almost flat and extensive plain, which is 60 - 300 m above mean sea level (Dickson and Benneh, 1995). The soils in the area have a high sand content with mean values of about 72 % in the topsoil (0-15 cm) and about 69 % in the subsoil (30-45 cm). The textural class is sandy clay loam at both soil levels (Agyare, 2004).

2.2. Hydrometeorological Measurements

The sensor types used to measure the water fluxes and the meteorological variables as well as the installation height above the land surface are given in Table 1. Sap flow was measured on selected cashew trees (diameters ranged from 16.8 cm to 18.2 cm and height varied between 5.2 m and 5.4 m) using constant heat sap flow sensors (Granier, 1985; 1987). Two cylindrical probes, about 2 mm in diameter, were implanted at breast height (1.3 m) in the sapwood of the tree trunks with previously installed aluminium tubes, separated vertically by 12 cm (Plate 1). The probes were installed on the north side of the tree, to minimise direct heating from sunshine, and then shielded with aluminium foil against rainfall. The downstream probe was continuously heated with a constant power source, whereas the unheated upstream probe served as a temperature reference. The dissipation of heat from the downstream heated needle increases with increasing sap flow rate. Temperature differences between the lower and the upper probes were converted to sap flow density with the empirical relationship validated for several tree species (Granier, 1987).

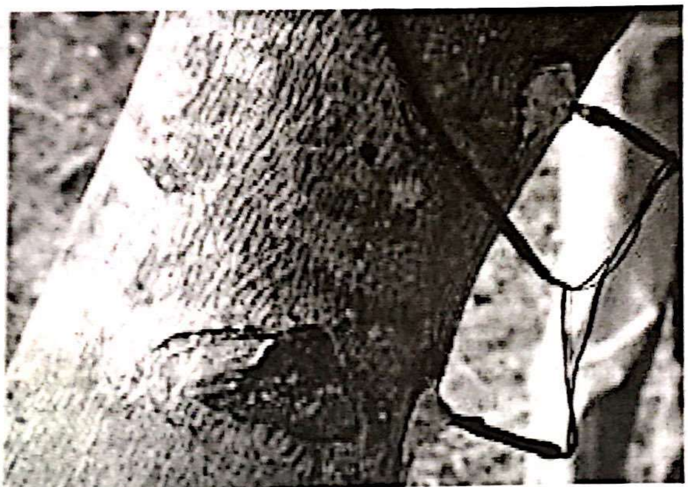

Plate 1: Sap flow sensors installed on a cashew tree at Ejura, Ghana

Table 1: Instrument used for measurement of hydrometeorology variables

Variable	Measurement height (m)	Instrument or sensor type	Sampling time
Solar radiation	3.5	SP LITE pyranometer (Kipp & Zonen)	10 s
Air temperature	2	50Y Temperature probe (Vaisala)	10 s
Relative humidity	2	50Y Relative humidity (Vaisala)	10 s
Wind speed	8	A100R vector instrument anemometer	10 s
Eddy vapour content	10	Krypton hygrometer (Campbell)	10 Hz
Sap flow	1.3	Granier sap flow system (UPGmbH)	10 s
Sensible heat flux	10	3-D sonic anemometer (Gill)	10 Hz

An eddy covariance system was used to measure latent and sensible heat fluxes over the orchard. This instrument was mounted at a height of 10 m on a tower installed in the middle of the experimental plot. The three directional components of wind speed were measured with a 3-D sonic anemometer (Gill Instruments Ltd., UK), whereas water vapour flux was measured with a Krypton hygrometer (model

KH_2O, Campbell Scientific, UK). Detailed description of the set up and operation of the device is given by Elbers (2002) and Schuttemeyer (2005). Meteorological variables, such as incoming solar radiation, net radiation, air temperature, relative humidity, wind speed and direction, were sampled at 10 s intervals and recorded as 10 min averages and were further integrated to 20 and 30 min averaging intervals. Eddy vapour flux data, sampled at a frequency of 10 Hz, were integrated over 10, 20, and 30 minute intervals; using ALTEDDY software (Elbers, 2002).

Meteorological data were used to compute the instantaneous evaporative demand function (E^*) following the procedure of Jarvis and McNaughton (1986). Estimated E^* was used as surrogate for eddy flux (E_c) for comparison purposes.

2.3 Data Analysis

Time lag was estimated by using (1) cross-correlation analysis (Oguntunde et al., 2004) and (2) a simple resistance-capacitance model (Phillips et al., 1997). Using cross-correlation analysis (CCA), time lags ranging from −120 to +120 min were introduced for each pair of time series and the corresponding range of correlation coefficients (R) was obtained with the cross-correlation function

$$R = \frac{Cov[X(t), Y(t+\tau)]}{\sigma_x . \sigma_y} \tag{1}$$

i.e. 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 standard deviations are given as:

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \mu_x)^2} \tag{2}$$

$$\sigma_y = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(Y_i - \mu_y)^2} \tag{3}$$

where μ_x and μ_y average values of the time series variables and n is sample size. 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; Post and Jones, 2001; Bond et al., 2002). In this study, this procedure was used for the same data set with different averaging intervals: 10 min, 20 min and 30 min, respectively. It is hypothesized that the accuracy of the estimated lag in this way would be affected significantly by the averaging frequency of the measurements. For example, lag for a time series pair with 20 min time steps will be accurate to the nearest 20 min.

Furthermore, given the large fluctuations characterising eddy covariance data, which lead to similar correlations over a wide range of lags (Phillips et al., 1997; Oguntunde et al., 2004), a test of equality of correlations near the maximum R was conducted using the Z-test (Oguntunde, 1998). Given the above problem with E_c, especially in conjunction with the CCA method, a more dynamic model is expected to bypass this dilemma. Hence a simple model of hydraulic resistance and capacitance was used. Briefly stated, the model consists of a simple resistance-capacitance network with above canopy transpiration representing the total current in the circuit and sap flow represents the current flowing through the main hydraulic partway of the tree stem. Details of this model are presented in Nobel (1983), Ogata (1987) and Phillips et al. (1997). Least squares regression of the model parameters was implemented by using a first order, four-stage instrument variable auto-regression algorithm (IV4 function, Matlab, Natick, Mass; Ljung, 1999). Both E_c from eddy covariance and E^* estimated were used inter-changeably with S_f as inputs to implement this IV4 function.

3. RESULTS AND DISCUSSION

3.1 Hydrometeorological Data

Daily mean and daytime maximum of meteorological variables are shown in Fig. 1. Daily mean solar radiation (R_s) ranged from 177 W m^{-2} (DOY 364) to 240 W m^{-2} (DOY 360) during the ten days of observation. The maximum daytime value of 865 W m^{-2} was recorded on December 24, 2002 (DOY 360). Mean air temperature, varied from 21.7 °C to 24.3 °C whereas the daily maximum varied between 30.7 °C and 33 °C. Relative humidity (RH) showed a marked variation during the observation period. Mean RH ranged between 34 % and 56 % on DOY 361 and DOY 364, but the highest daytime value of 88 % was recorded on DOY 01(January 1, 2003). Wind speed is generally low in this area varying between 0.9 m s^{-1} and 1.6 m s^{-1}, and the daytime maximum was normally below 3 m s^{-1}. There was no rainfall event during the 10-day measurement period.

Diurnal time series of eddy vapour flux (E_c), evaporative demand (E^*), and xylem sap flow (S_f) are shown in Fig. 2 for the ten days of measurement using the most frequent sampling (AI = 10 min). E_c and E^*, shown in Fig. 2A, revealed the highly fluctuating characteristic of eddy correlation flux as compared to the estimated canopy transpiration based on meteorological data. A slight phase shift can be noticed between the fluxes. Sap flow and E_c are especially correlated during the rising limb. The falling limb showed a more prolonged water uptake by the trees even when E_c has ceased (Fig. 2B). The possible effect of temporal averaging intervals (10 min, 20 min, and 30 min) on S_f, E_c, E^* and R_s are shown in Fig. 3. The pattern of R_s was only slightly influenced, whereas E_c shows a marked fluctuation, which smoothens-out as the AI increased. The effect of AI on the diurnal pattern of $E^*$and S_f was not as pronounced. On the typical day shown in Fig. 3 (December 27, 2004), the pattern of E^* merely followed the solar radiation and R_s reached its peak value about mid-day (around 12:20 and 12:30 h local time). Xylem flux rapidly increased and reached the peak about the mid-morning and decreased slowly thereafter to near zero values after 20:00 h. The shape of the E_c curve is somewhat different from those of S_f and R_s. E_c rises quite early, the remains near the maximum for an extended part of the day, after which it decreases to zero faster than all other variables.

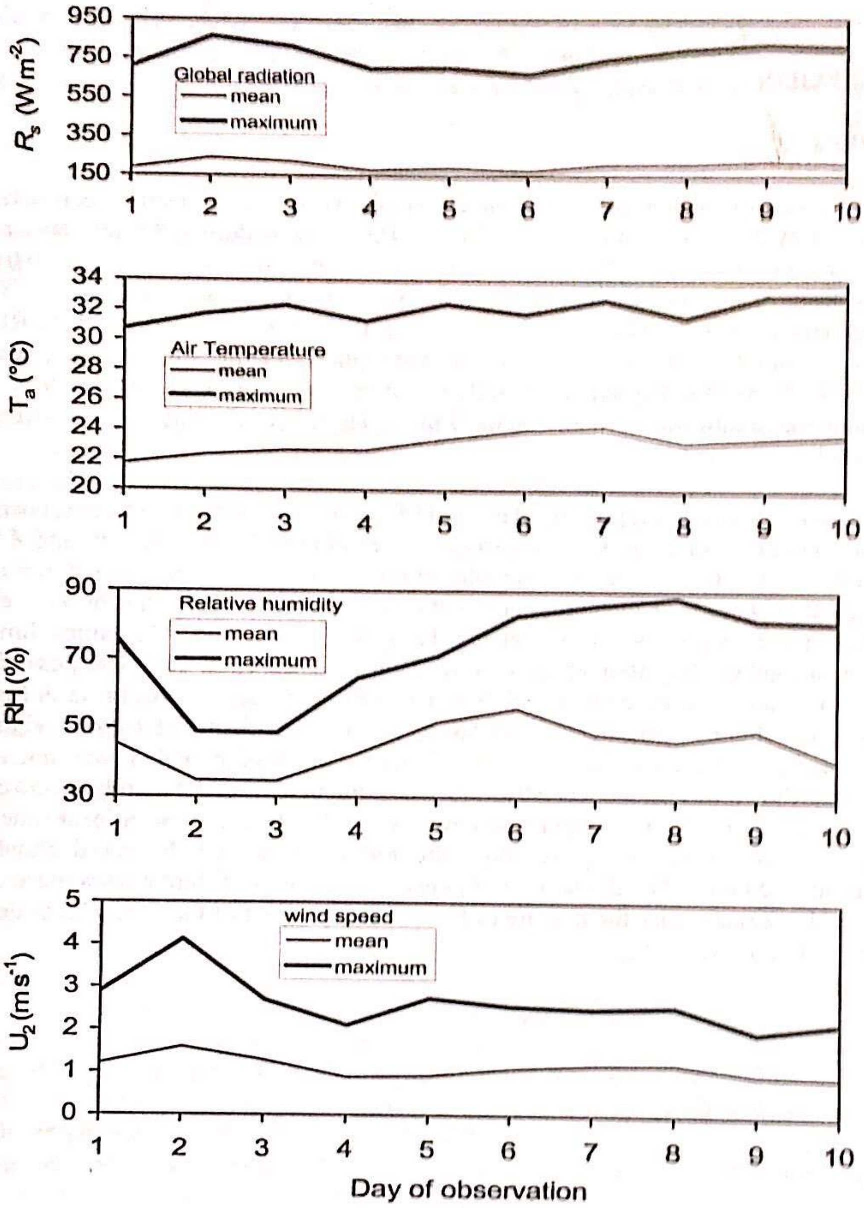

Fig. 1. Meteorological data for the measurement period (December 24, 2002 to January 03, 2003), reading from the top: solar radiation (R_s), air temperature (T_a), relative humidity (RH), and wind speed (U_2), respectively. Daily averages (thin line) and diurnal maximum (thick line) (day 1 = Dec. 24, 2002).

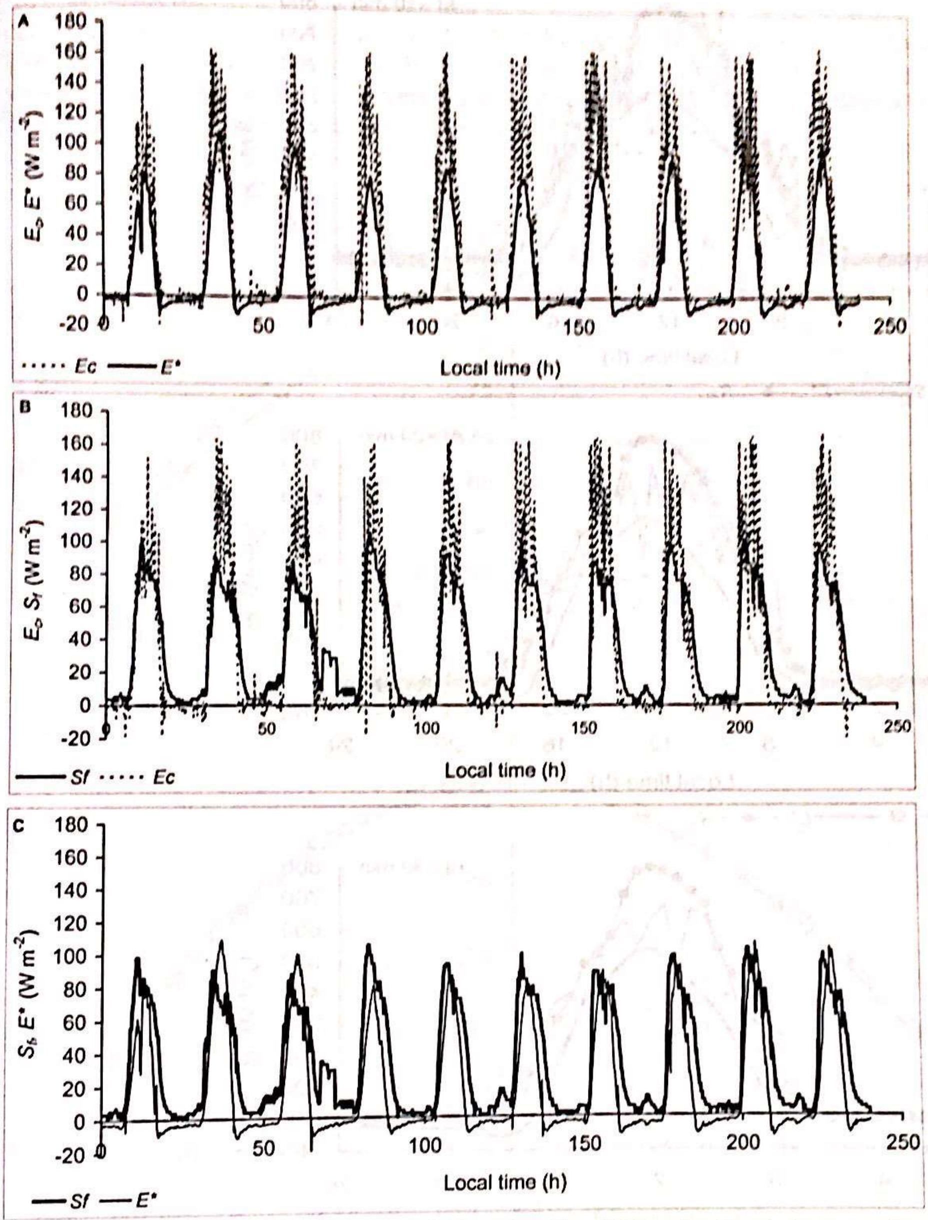

Fig. 2. Time series of diurnal courses of (A) eddy flux (E_c) and estimated canopy transpiration (E^*), (B) xylem sap flow (S_f) and eddy flux (E_c); and (C) xylem sap flow (S_f) and estimated canopy transpiration (E^*), using the AI =10 min series, for the observation period.

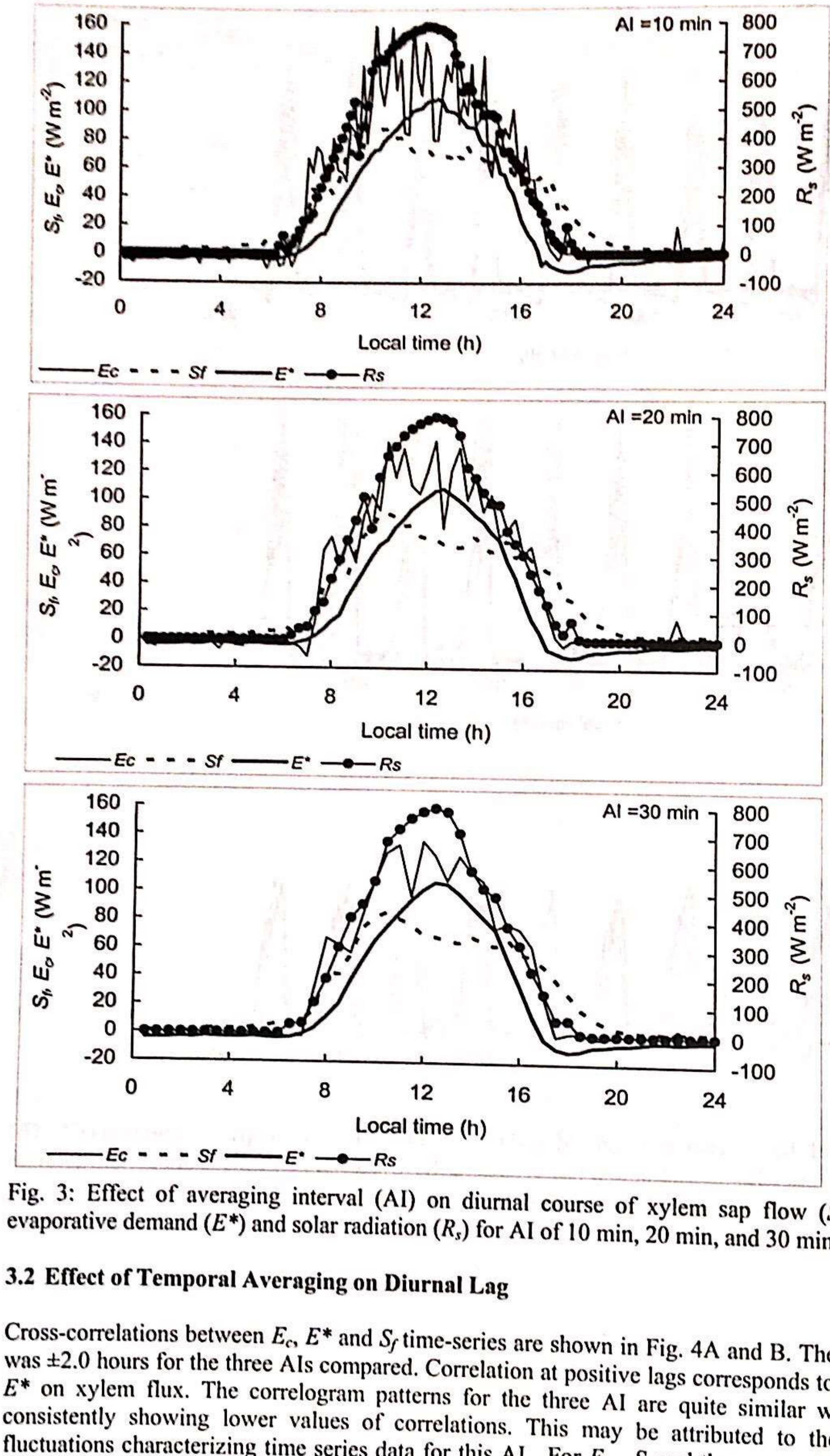

Fig. 3: Effect of averaging interval (AI) on diurnal course of xylem sap flow (S_f), eddy flux (E_c), evaporative demand (E^*) and solar radiation (R_s) for AI of 10 min, 20 min, and 30 min, respectively.

3.2 Effect of Temporal Averaging on Diurnal Lag

Cross-correlations between E_c, E^* and S_f time-series are shown in Fig. 4A and B. The range of lags used was ±2.0 hours for the three AIs compared. Correlation at positive lags corresponds to an influence of E_c, E^* on xylem flux. The correlogram patterns for the three AI are quite similar with the 10 min AI consistently showing lower values of correlations. This may be attributed to the highest observed fluctuations characterizing time series data for this AI. For E_c - S_f and the range of lags introduced, the ccf (Eq.1) yields R values that vary from: 0.60-0.89 (AI=10min), 0.60-0.90 (AI=20min), and 0.62-0.94 (AI=30min), with each AI showing different lag at maximum R. The most intensive averaging interval shows that S_f lags E_c by 10 min whereas the time-series based on 20 min AI yielded a lag of 20 min while 30 min lag was observed for time-series based on AI of 30 min.

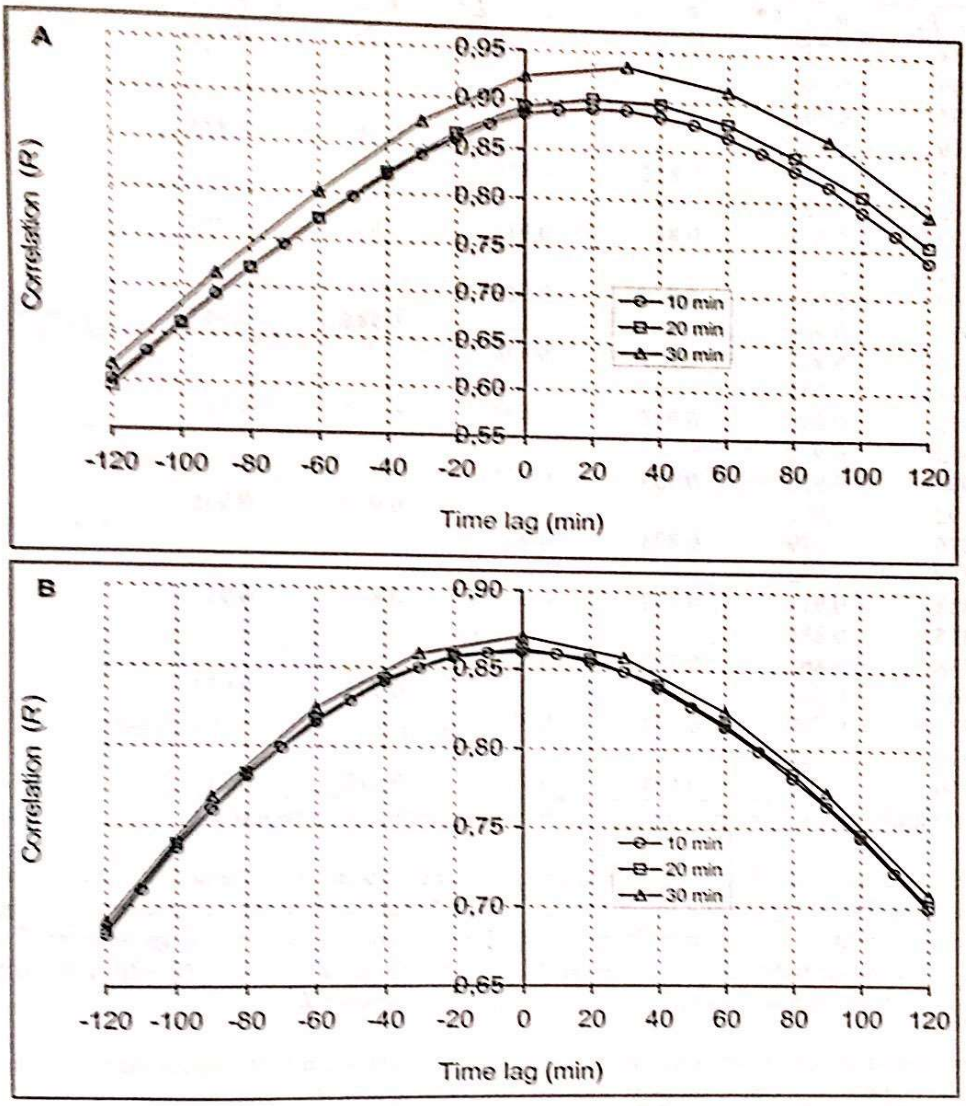

Fig. 4. Cross-correlation between (A) eddy vapour flux (E_c) and stem water flux (S_f) and (B) evaporative demand (E^*) and stem water flux (S_f). Correlation at positive lags mean stem water flux lags behind the other variable.

Lags between R_s, E_c, and E^* for the three AI are presented in Table 2. The range of correlations observed for the R_s - E^* pair were consistently higher than for R_s-E_c, and also increased with AI. R_s was found to lag E_c by 10 min (R=0.92; AI=10 min), 20 min (R=0.92; AI=20 min) and 0 min (R=0.95; AI=30 min), for the three AIs, respectively. However, there was no lag between R_s - E^* series for all the AIs. The range of R-values obtained from cross-correlation analysis (Eq.1) for the R_s -S_f time-series pairs are presented in Table 3. The result shows that sap flow exhibits maximum R at a lag of 10 min for AI = 10 min, but zero lag for AI = 20 and 30 min.

Table 2. Cross-correlation between solar radiation (R_s), above-canopy eddy vapour flux (E_c), and estimated canopy transpiration (E^*) for AI of 10 min, 20 min, and 30 min, respectively. Correlations at positive lags mean R_s leads the other variable.

Time Lag (min)	†Correlation coefficient (*R*) AI = 10 min		AI = 20 min		AI = 30 min	
	R_s vs E_c	R_s vs E^*	R_s vs E_c	R_s vs E^*	R_s vs E_c	R_s vs E^*
-120	0,738	0,729	0,751	0,73	0,78	0,731
-110	0,769	0,766				
-100	0,794	0,801	0,806	0,802		
-90	0,819	0,833			0,86	0,835
-80	0,841	0,863	0,851	0,864		
-70	0,862	0,89				
-60	0,877	0,913	0,887	0,915	0,915	0,916
-50	0,891	0,934				
-40	0,902	0,951	*0,910*	0,952		
-30	*0,912*	0,964			*0,946*	*0,967*
-20	*0,918*	0,975	*0,923*	*0,976*		
-10	*0,921*	*0,982*				
0	*0,919*	*0,986*	*0,921*	*0,987*	*0,950*	*0,987*
10	*0,915*	*0,982*				
20	*0,905*	0,974	*0,905*	*0,975*		
30	0,892	0,963			0,917	0,965
40	0,876	0,949	0,873	0,95		
50	0,859	0,932				
60	0,838	0,911	0,832	0,913	0,858	0,913
70	0,815	0,888				
80	0,788	0,861	0,782	0,862		
90	0,76	0,831			0,775	0,833
100	0,73	0,799	0,721	0,801		
110	0,698	0,765				
120	0,666	0,728	0,654	0,73	0,675	0,73

†All italicized correlations in each column are not significantly different from each other.

The results of a more robust method, a simple resistance-capacitance model, are presented in Table 4. The results show a time lag that was generally lower than 10 min. E^* was found to lag E_c by about 3.1 min, 2.5 min and 2.1 min, respectively for 10 min, 20 min, and 30 min averaging intervals. Lags between E_c - S_f pairs showed a decreasing order, from 6.4 min at AI =10 min to about 2 min at AI =30 min, with increasing AI. Similar trends, but with lower values, were estimated between E^* - S_f.

Table 3. Result of cross-correlation between solar radiation (R_s) and stem sap flow (S_f) for AI of 10 min, 20 min, and 30 min, respectively. Correlations at positive lags mean S_f lags R_s

Time lag (min)	†Correlation coefficient (*R*) AI = 10 min	AI = 20 min	AI = 30 min
-120	0,698	0,701	0,707
-110	0,729		
-100	0,757	0,759	
-90	0,783		0,792
-80	0,807	0,809	
-70	0,829		
-60	0,849	0,85	0,858
-50	0,866		
-40	0,881	0,883	
-30	0,894		*0,903*

		r	
-20	0.903	0.905	
-10	0.911		
0	0.915	0.917	0.925
10	0.916		
20	0.914	0.916	
30	0.909		0.918
40	0.901	0.904	
50	0.891		
60	0.878	0.88	0.887
70	0.864		
80	0.845	0.847	
90	0.825		0.825
100	0.804	0.806	
110	0.780		
120	0.755	0.757	0.764

[1] All italicized correlations in each column are not significantly different from each other.

Table 4. Results of the time lags estimated between above canopy eddy vapour flux (E_c) and estimated canopy transpiration (E^*), above canopy eddy vapour flux (E_c) and stem sap flow(S_f), and estimated canopy transpiration (E^*) and stem sap flow(S_f) for Δt of 10 min, 20 min, and 30 min, respectively.

Paired variables	Time lag (min) *Δt = 10 min	Δt = 20 min	Δt = 30 min
E_c vs E^*	3.1	2.5	2.1
E_c vs S_f	6.6	4.1	1.9
E^* vs S_f	1.2	0.2	0.2

*Δt is averaging interval

4. DISCUSSION AND CONCLUSIONS

The observed differences in time lag for the respective Δts demonstrate the range of possible results obtainable using time series based on different Δts. The accuracy of the lag estimates may largely depend on the temporal resolution of the paired variables. Because of large variations in eddy fluxes, a cross-correlation analysis of E_c – S_f showed a broad range of statistically similar high correlations over a range of lags. According to the Z test for equality of correlations, lags from 0 min to ~40 min (Δt=10), 0 min to ~40 min (Δt=20), and 0 min to ~30 min (Δt=30) were not significantly different from one another. Making the right choice of accurate time lags very difficult since though by visual inspection the lag corresponding to the maximum r could be selected, from a statistical standpoint, every lag within the range of r similarities may be chosen. In contrast, for time series pair E^* – S_f, although lags showed a broad range of similar correlations over a range of lag intervals, the three Δt yielded zero lag at maximum r. Using a similar cross-correlation analysis, Phillips et al. (1997) have reported weak correlation over a broad range of positive and negative lags in a loblolly pine. This broad range was attributed to large variations in vertical vapour flux of the eddy correlation data as compared to the xylem flux. Loustau et al. (1996) also reported the difficulty associated with comparing sap flow data with vapour flux measured with eddy correlation. However, estimated canopy transpiration calculated from meteorological variables did not show fluctuations of the magnitude observed in eddy fluxes. It rather has a pattern similar to radiation.

Results from the resistance capacitance model seem to be more reliable. The lags of less than 10 min lag estimated with this method are much more realistic if one critically examines the time series plots shown in Fig. 3 and 4. Visual inspection showed clearly that the lags between all the compared series were all really less. These less values may be connected with the fact that during the dry wet transition period, in which this study was conducted, soil water is not limiting. It is expected that the time lag in night-time recharge of stem capacitance would increase with drying soil moisture conditions. Average soil moisture, between 60 cm to 100 cm soil depth, in the experimental plot was in the order of 0.25 to 0.30 m^3 m^{-3}. Furthermore, the discrepancies noted with the lags estimated between E_c - S_f and E^* - S_f may be connected with the fact that E^* also lagged behind E_c. This indicates that caution should be applied when using evaporative demand as a surrogate to the above-canopy transpiration measurement as this may lead to errors in the estimate of time lag. The general decreasing trend of estimated lag with increasing AI showed the potential for error in using paired series with longer sampling intervals than the actual lag present in a given soil-plant-atmosphere system. Unfortunately, the actual time lag needed for the purpose of estimating canopy transpiration and conductance from xylem sap flow data, are not know a priori. The results of this study suggest that in young cashew trees under non-limiting soil water conditions, sap flow data may be used to estimate transpiration at time scales longer than 10 min, but that on time scales of less than 10 min, the effects of hydraulic resistance and capacitance may decouple instantaneous canopy transpiration from the xylem sap flow.

In conclusion, the influence of the length of AIs of the hydrometeorological variables, as well as the evaporative demand, in the determination of lag time between vertical vapour and xylem sap fluxes, including both fluxes with solar radiation have been investigated. The results indicated that the accuracy of the estimated time lag was highly dependent on the temporal resolution or averaging interval of the variables involved. An intensive AI of less than five minutes may be suggested to be used as the averaging frequency in the estimation of time lag in trees. The study further suggests that using meteorological transpiration as surrogate for actual above-canopy transpiration may be misleading.

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