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# Partitioning energy and evapo-transpiration above and below a tropical palm canopy

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## Abstract

For open canopies, the partitioning of energy and water fluxes between the upper canopy and the under-storey is key to understand the competition mechanisms between layers. We monitored stand evapo-transpiration by eddy-covariance ( $E$ ), tree transpiration ( $T$ ) by heat-dissipative sapflow, soil ( $G$ ) and stand ( $J$ ) heat storage during 3 years in a typical coconut palm row-plantation of the humid tropics, displaying a constant leaf area index (LAI = 3) and a grass under-storey. A two-level flux experiment yielded cross-validation of the evapo-transpiration of the under-storey ( $E_u$ ) with  $E - T$ , through energy balance closure for  $E$  and sapflow calibration in the laboratory for  $T$ . On a yearly time step,  $E$  represented 40% of rainfall, the sensible heat flux ( $H$ ) was 26% of net radiation and the Bowen ratio was 0.39, all indicating that water availability was close-to-optimum.  $T$  represented 68% of  $E$ , close to the 75% of soil coverage by palms. The inter-annual variability was low for potential evapo-transpiration ( $ET_o$ ), energy and water fluxes. The seasonal variability was more pronounced, driven by radiation and vapour pressure deficit (VPD). The canopy conductance of coconut palms appeared to be strongly controlled by VPD. Given its constant LAI, its continuous growth and its simple architecture, the coconut palm appears to be an ideal candidate for physiological work and agroforestry modelling. © 2006 Elsevier B.V. All rights reserved.

*Keywords:* Sapflow calibration; Eddy-correlation; Energy balance closure; Agroforestry; *Cocos nucifera* L

## 1. Introduction

The contribution of terrestrial ecosystems to global carbon budgets is being assessed through a network of

more than 200 eddy-flux towers (FLUXNET) installed over various canopies. Most experiments have been conducted on temperate forests. Few are available in tropical ecosystems, despite recent investments (LBA, Ameriflux, AsiaFlux, Oznet, KoFlux). Few have been carried out over crops, e.g. sugar cane (Ameriflux and Oznet), paddy rice (AsiaFlux and KoFlux), or some arable lands (Carboeuroflux). Due to the rapid extension

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## Nomenclature

$A$	conductive area of stem ring (m)
$C$	soil volumetric heat capacity ( $\text{J m}^{-3} \text{K}^{-1}$ )
$d$	displacement height (m)
$D$	vapour pressure deficit (VPD) at reference height (h Pa)
$D_p$	coconut palm density (tree $\text{ha}^{-1}$ )
$E$	evapo-transpiration of the stand ( $\text{mm h}^{-1}$ )
$E - E_u$	coconut palm canopy transpiration ( $\text{mm h}^{-1}$ )
$ET_o$	Penman–Monteith theoretical evapo-transpiration ( $\text{mm h}^{-1}$ )
$E_u$	evapo-transpiration of the under-storey ( $\text{mm h}^{-1}$ )
$F$	sapflow density ( $\text{m}(\text{H}_2\text{O})^3 \text{m}(\text{A})^{-2} \text{s}^{-1}$ ) or else ( $\text{mm s}^{-1}$ )
$g_c$	canopy conductance ( $\text{mm s}^{-1}$ )
$G$	soil heat flux ( $\text{W m}^{-2}$ )
$H$	sensible heat flux of the stand ( $\text{W m}^{-2}$ )
$I$	interception of rainfall ( $\text{mm h}^{-1}$ )
$J$	heat storage in the stand ( $\text{W m}^{-2}$ )
$K$	sapflow index
$K_c$	crop coefficient = $E/ET_o$
$l$	leaflet dry mass-to-area ratio (LMA) ( $\text{kg m}^{-2}$ )
$L$	leaf area index ( $\text{m}(\text{leaf})^2 \text{m}(\text{soil})^{-2}$ )
$M_1$	dry mass of leaflets per leaf (kg)
$n$	natural frequency (Hz)
$q$	air humidity ( $\text{mmol}(\text{H}_2\text{O}) \text{m}^{-3}$ )
$Q_p$	incident photosynthetic photon flux density ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )
$R_i$	leaf rank = 1 for newly emitted leaf and incrementing towards bottom on crown
$R_n$	net all-wave radiation flux density measured at reference height ( $\text{W m}^{-2}$ )
$S$	spectral density
$T$	temperature ( $^{\circ}\text{C}$ or K)
$T$	transpiration of the coconut palms ( $\text{mm h}^{-1}$ )
$w$	vertical wind velocity ( $\text{m s}^{-1}$ )
$z_m$	measurement height (m)

### Greek letters

$\alpha$	first coefficient for sapflow density calibration ( $\text{m}(\text{H}_2\text{O})^3 \text{m}^{-2} \text{s}^{-1}$ )
$\beta$	second coefficient for sapflow density calibration
$\lambda E$	latent heat flux of the stand ( $\text{W m}^{-2}$ )
$\theta$	soil volumetric water content ( $\text{m}(\text{H}_2\text{O})^3 \text{m}(\text{soil})^{-3}$ )

$\sigma$	variance
$\tau$	output period of CS615 probes (ms)

### Sub/super-scripts

'	fluctuation
a	air or sensible in air
c	calibrated
g	Granier (1985) standard
m	maximum value
p	coconut palm
s	soil
u	under-storey
v	vegetation
w	latent in air

of tropical perennial crops over the last 40 years, the impacts on local environments require further studies (biodiversity,  $\text{H}_2\text{O}$  and C balance, soil fertility, erosion, etc.) in order to successfully adapt management strategies to sustainability. In this study, we focused on a major tree-crop from the humid tropics, the coconut palm, which represents 23% of the total tropical perennial crop plantations world-wide (47 M ha: FAO, 2003). Coconut plantations can be mono-specific or associated with under-storey crops or cattle (agroforestry systems).

There is a lack of information regarding energy fluxes and water requirements at the scale of coconut palm plantations and across seasons, although, at plant and organ scales, important physiological studies have been dedicated to water relations (Kasturibai et al., 1988; Repellin et al., 1997; Jayakumar et al., 1988) and drought tolerance (Voleti et al., 1990; Rajagopal et al., 1990; Braconnier and D'auzac, 1990; Braconnier and Bonneau, 1998). Light transmission to under-storey crops has been documented with the purpose of agroforestry applications (Dauzat and Eroy, 1997; Mialet-Serra et al., 2001) but the partitioning of water fluxes between the coconut palm canopy and the under-storey is unknown despite its considerable importance for understanding water requirements and competition mechanisms with under-storey crops. In Vanuatu (Oceania), growth conditions are very favourable and results are expected to provide data for unstressed cultivation conditions, which can be used as a reference for further comparison with stressed conditions.

Ecosystem water distribution and flows can be assessed by soil water balance, sapflow, or more recently by eddy-covariance techniques (Aubinet et al., 2000). The components of evapo-transpiration and the spatial scale encompassed by each technique were

summed up by Wilson et al. (2001). Taken separately, these techniques usually suffer from calibration and scaling problems, when combined, their reliability is enhanced. The present study proposes a combined approach including calibration steps, aiming at cross-validation of eddy-covariance and sapflow methods. The measured evapo-transpiration fluxes ( $E$ ) can be validated through a complete energy balance assessment. The energy balance closure is expected to be close-to-optimum under conditions where horizontal advection is minimum, with a flat terrain and large fetch. Four main methods for measuring plant transpiration by sapflow ( $T$ ) are available and have been widely documented on various species (e.g. Granier et al., 1996; Lu et al., 2004). The heat dissipation method (Granier, 1985, 1987) has proved to be easy to use and suitable for long term monitoring, especially on large stems. However, some reports clearly underestimate sapflow, and others stress the need to specifically calibrate the heat dissipation method wherever the original calibration has not been verified (Smith and Allen, 1996; Lundblad et al., 2001). Calibration of the probes in the laboratory against the gravimetric method is recommended if the probes are built differently from the original model (Wilson et al., 2001). Additionally, the interaction between the probe and the conductive area may require a specific calibration in the field, especially if the probes are suspected to be in partial contact with non-active xylem (Clearwater et al., 1999). It is a major concern in palms, due to the scattered distribution of fibro-vascular bundles in the stem tissue (Tomlinson, 1961).

Direct comparisons of  $T$  and  $E$  have often been reported to be consistent (e.g. Granier et al., 2000; Saugier et al., 1997). Eddy-covariance can even provide a reliable calibration tool for sapflow, provided that the contribution of the under-storey ( $E_u$ ) is accurately assessed. Validating the measurements of  $E_u$  below the canopy is challenging. Turbulent spectra measured below the canopy may eventually differ from those associated with fluid flow above the canopy due to short-circuiting of the inertial cascade (Baldocchi and Meyers, 1991) and to the intermittency of turbulence, resulting from the strong wind shear at the top of the canopy (Kaimal and Finnigan, 1994). The reliability of eddy-covariance measurements below the canopy can eventually be assessed by energy balance closure. However, the comparison of fluxes with the proper net radiation below the canopy may appear cumbersome, due to fetch uncertainties. Consequently, relatively few studies report direct measurements of rates and controlling processes over the soil system under vegetated canopies (e.g.

Saugier et al., 1997; Baldocchi and Meyers, 1991; Baldocchi et al., 2000; Wilson et al., 2001).

In sparse or row-crops such as coconut plantations, the degree of aerodynamic mixing is likely to be greater than for closed canopies, which appears favourable for turbulence issues below the canopy. On the other side, the variability of light transmission to the under-storey is worsened below open canopies, so that fetch uncertainties and horizontal variability of net radiation become severe impediments to the energy balance closure method. In such conditions, we assumed that a validation of measured  $E_u$  by  $E - T$  (where  $E$  and  $T$  are both validated independently) would be more achievable than through energy balance closure.

The main objectives of the present study are to quantify energy budget and water transfer within a tropical coconut palm plantation. The study was specifically designed: (i) to evaluate the reliability of eddy-covariance measurements above and below the canopy through energy balance closure and spectral analysis, (ii) to cross-validate  $T$  and  $E - E_u$  and (iii) to describe the seasonal and inter-annual variability of the energy balance and the partitioning of evapo-transpiration between the canopy of coconut palms and the under-storey.

## 2. Materials and methods

### 2.1. Location, climate and stand

The coconut plantation (15°26.6'S, 167°11.5'E) was part of the Vanuatu Agricultural Research and Technical Centre (VARTC), covering around 400 ha at Espiritu Santo, Vanuatu, South Pacific. The climate was tropical and humid. Annual rainfall from 1983 to 2003 was 2763 mm year<sup>-1</sup> ( $\pm 826$  mm year<sup>-1</sup> S.D.), peaking during the warm and rainy season (December–April), with an average of 327 mm month<sup>-1</sup>. A cooler season usually occurred from June to September, with an average of 119 mm of rainfall month<sup>-1</sup>. The monitoring period lasted 36 months (3 years) between October 2001 and September 2004. During the warm and cool seasons, respectively, the monthly mean of global radiation ranged from 23 to 10 MJ m<sup>-2</sup> day<sup>-1</sup>, of air temperature from 26 to 23 °C, and of vapour pressure deficit from 6 to 4 h Pa.

The experimental stand was located 3 km away from the seashore and 80 m above sea level. The soil characteristics of the stand and its surroundings were surveyed by Bonzon et al. (1991) and corresponded to Nitisol (WRB, 1998). The soil profiles originated from ancient volcanic ashes, deep by 1–2.5 m and overlying limestone. Clay and fine silts accounted for more than

80% of the total. The nutritional characteristics of these ferralitic and slightly desaturated soils were reported excellent (Quantin, 1978). Slope, surface runoff and stone content were close to zero. No cyclone or El-Niño event affected the present experiment.

The stand characteristics are shown in Table 1. The stand was row-planted in 1983 with the Vanuatu Red Dwarf × Vanuatu Tall hybrid coconut variety (Labouisse et al., 2005). The planting design was triangular and equilateral (alternating N–S rows), with a planting density of 160 tree ha<sup>-1</sup> in 1983 and a residual density of 144 tree ha<sup>-1</sup> in 2001. More than 20 grass species composed the under-storey, with mainly *Paspalum* sp. (21% of soil coverage), *Mimosa pudica* (11%), *Desmodium heterophyllum* (9%), *Mikania micrantha* (9%) and *Sida* sp. (8%).

## 2.2. Leaf area index of coconut and grass canopies

The leaf area index of coconut palm ( $L_p$ ) was assessed by destructive method and by monitoring on living

plants. Prior to experiment, 10 coconut palms were felled and their leaves (fronds composed of leaflets) counted, from ‘rank’ 1 (newly emitted leaf at the top of the unique bud) to, e.g. ‘rank’ 32 at the bottom of the crown. Seven leaves per coconut palm were sampled to measure the leaflet dry mass per leaf ( $M_l$ ) and the leaflet dry mass-to-area ratio (LMA:  $l_p$ ), both related empirically to leaf rank. We computed the total area of every leaf of the 10 palms as the ratio of  $M_l$  to  $l_p$  and  $L_p$  was derived. The number of leaves and the leaf emission rate were monitored every month on 10 living palms in order to assess the eventual seasonal variations of  $L_p$ . The leaf area index of grass ( $L_u$ ) was measured in May 2003 during maximum grass development, prior to periodic (2 months) slashing of the clear inter-row. Three replicated plots, taken to be representative of the horizontal variability of the whole stand in terms of the windrow, row and clear inter-row sub-plots and covering a total 24 m<sup>2</sup> of soil were sampled. The grass aboveground dry mass was measured on a sample corresponding to around 5% of the total. Grass LMA ( $l_u$ ) was measured and used for estimating  $L_u$ .

Table 1  
Main features of the experimental stand, coconut palms and grass under-storey

Description	Coconut palms monitored for sapflow (N = 10)	Coconut palms sampled for biomass and LAI (N = 10)	Whole stand of coconut palms (N = 866)	Grass
Initial/remaining planting density (tree ha <sup>-1</sup> )	–	–	160/144	–
Planting distance on the line/between lines (m)	–	–	8.5/7.36	–
Area of experimental stand/with border trees (ha)	–	–	6.0/8.2	–
Number of similar stands attached upwind	–	–	3	–
Diameter at breast height (cm)	28.11 ± 1.17 S.D.	30.38 ± 2.52 S.D.	N.m.	–
Stem basal area, debarked (m <sup>2</sup> ha <sup>-1</sup> )	8.31	N.m.	N.m.	–
Height at leaf rank 14 (August 2000)	10.9 ± 1.0 S.D.	11.2 ± 0.97 S.D.	10.8 ± 1.3 S.D.	–
Height at tip of leaf rank 1 (m)	N.m.	N.m.	16 (estimated)	–
Leaf count per tree (cool season, July 2003)	32.3 ± 1.64 S.D.	N.m.	N.m.	–
Leaf count per tree (rainy season, March 2004)	32.3 ± 1.34 S.D.	N.m.	N.m.	–
Leaf emission period (days, averaged over 2 years)	28	N.m.	N.m.	–
Leaf lifespan (months)	30	N.m.	N.m.	–
Average leaflet dry mass per leaf (kg)	N.m.	1.34 ± 0.27 S.D., N = 66 leaves	N.m.	–
Average leaflet LMA, $l_p$ (kg m <sup>-2</sup> )	N.m.	0.208 ± 0.03 S.D., N = 104 leaflets	N.m.	–
Average leaf area (m <sup>2</sup> leaf <sup>-1</sup> )	N.m.	6.41	N.m.	–
Average plant leaf area (m <sup>2</sup> tree <sup>-1</sup> )	N.m.	205.1	N.m.	–
LAI of coconut palms, $L_p$ (m(leaf) <sup>2</sup> m(soil) <sup>-2</sup> )	N.m.	2.95	N.m.	–
Canopy coverage index (m(proj.canopy) <sup>2</sup> m(soil) <sup>-2</sup> )	N.m.	0.75 (estimated)	N.m.	–
Grass LMA, $l_u$ (kg m <sup>-2</sup> )	–	–	–	0.045 ± 0.003 S.D. (N = 3 plots)
Grass min/max/average LAI, $L_u$ (m(leaf) <sup>2</sup> m(soil) <sup>-2</sup> )	–	–	–	1.95/3.5/2.7 ± 0.3 S.D. (N = 3 plots)

The coconut palms were 20 years old in 2003. LAI: leaf area index; LMA: leaf dry mass-to-area ratio; N: number of samples; N.m.: not measured; S.D.: standard deviation.

### 2.3. Eddy-covariance, climate and potential evapotranspiration ( $ET_o$ )

The experiment was set up in accordance with the Carboeuroflux recommendations (Aubinet et al., 2000). Eddy-covariance measurements were performed continuously above the canopy (22 m) and also for two short periods below the canopy (5.5 m) during two-level flux experiments. This 5.5 m elevation was a compromise, where no foliage was present between the floor and the measurement height, and as high as possible in order to enlarge the footprint and minimise sampling errors associated with radiation and flux heterogeneity over the soil. 3D wind components and temperature were measured with a WindMaster Pro ultrasonic anemometer (Gill Instruments, Lymington, UK) at 10 Hz.  $H_2O$  fluctuations were measured with a Li-7500 open path (LiCor, Lincoln, NE, USA), calibrated either with a dew point generator (Li-610, LiCor) or a MP103A, temperature and relative humidity probe (Rotronic, Bassersdorf, Germany). A Young 8100 sonic anemometer 20 Hz (R.M. Young Company, MI, USA), was also used during the two-level flux experiment. Raw data were collected and pre-processed by “Tourbillon” software (INRA-Bioclimatologie, Bordeaux, France) for a time-integration period of 300 s. Raw data were post-processed using EdiRe software (University of Edinburgh, UK) into half-hourly values. All data were despiked according to variance filters, the axes were rotated three times in order to fit the “natural wind coordinate system” (McMillen, 1988; Lee et al., 2004), all data were linear-detrended, and vapour fluxes were corrected for buoyancy (Webb et al., 1980).

Regarding fetch and footprint, the stand was surrounded upwind (referring to the south-eastern Trade Winds) by similar coconut stands, covering over 32 ha. The eddy-covariance tower was placed in the downwind last third portion of the stand. The slope was nil. We selected all data from 2003 above the coconut palm canopy in near-neutral conditions, used the logarithmic law of wind profile (Kaimal and Finnigan, 1994) and derived a roughness height of 1.4 m (taking a measurement height,  $z_m$ , of 22 m, a canopy height of 16 m, and a displacement height,  $d$ , of 14.2 m, the latter estimated according to Ogée, 2000). A footprint study (according to Hsieh et al., 2000, using 80% of the ratio of scalar to surface fluxes) indicated that the fetch fell within the distance tower-transition in the direction of the wind for 72% of all half-hourly diurnal values of 2003. Alternatively, the ratio of the distance tower-transition to  $(z_m - d)$  fell between 20 and 230 (depending on azimuth): this ratio is expected to be

larger than 10, or preferably larger than 20, considering that scalar flux source areas are smaller than scalar concentration source areas by approximately an order of magnitude, and that the rule-of-thumb threshold of 100 would be inadequate and updated (Schmid, 1997). Both approaches led to the conclusion that it was not necessary to filter our raw data for fetch.

Fourier’s transforms were applied to 30 min records of 10 Hz turbulence data to examine the spectral features of vertical wind velocity ( $w$ ), air temperature ( $T$ ) and air humidity ( $q$ ) above and below the canopy using the same combination of Gill MasterPro and Li7500 instruments. Half-hourly samples were selected between 10:00 a.m. and 02:30 p.m. on three consecutive days, under neutral thermic conditions (stability close to zero) and for similar wind-speed ( $2.7 \text{ m s}^{-1}$  above the canopy and  $0.55 \text{ m s}^{-1}$  below the canopy). The three samples were averaged.

Climate variables were logged at reference height (22 m) on a CR10X and AM416 Multiplexer (Campbell Scientific, Shepshed, UK). The measurement period was 30 s, integrated half-hourly. They were measured using the following devices: global radiation: silicon cell pyranometer SKS1110 (Skye Inst. Ltd); net radiation: NR-Lite (Kipp & Zonen, Delft, The Netherlands); incident photosynthetic photon flux density ( $Q_p$ ): home-made probe (Dauzat and Eroy, 1997) calibrated against commercial probes; temperature and humidity: MP103A (Rotronic, Bassersdorf, Germany); rainfall tipping-bucket: ARG100 (R.M. Young, MI, USA); wind-speed and direction: 03001 Wind Sentry ARG100 (R.M. Young, MI, USA). The theoretical evapo-transpiration from a wet grass placed under local climate conditions,  $ET_o$ , was computed in accordance with FAO (1998).

### 2.4. Energy balance

The energy balance of the stand could be expressed on an instantaneous time-scale as

$$R_n = H + \lambda E + G + Q \quad (1)$$

where  $R_n$  is the net radiation,  $H$  the sensible heat flux,  $\lambda E$  the latent heat flux,  $G$  the soil heat storage and  $J$  is the storage in the air (heat and latent) and in the biomass. All terms were expressed as energy flux densities in  $\text{W m}^{-2}$ .

### 2.5. Soil temperature, water content and heat storage

Soil temperature and humidity were assessed throughout three soil profiles, adopted in accordance



with the horizontal field heterogeneity, in the windrow, the row and the clear inter-row. Soil temperature profiles were measured using  $0.2 \times 10^{-3}$  m copper-constantan TC leads buried at 0.02, 0.04, 0.06, 0.16, 0.32, 0.64 and 1 m, using a 10TCRT thermistor as reference. Soil volumetric water content ( $\theta$ :  $\text{m}(\text{H}_2\text{O})^3 \text{m}(\text{soil})^{-3}$ ) was measured using 21 water content reflectometers (CS615 probes, Campbell Scientific, Shepshed, UK), buried horizontally in the vertical walls of the trenches at 0.07, 0.15, 0.30, 0.60, 1, 1.5 and 2 m. The measurement period was 30 s, averaged half-hourly using a CR10X and two AM416 Multiplexers (Campbell Scientific, Shepshed, UK). Due to the high clay content of the soil, it was necessary to calibrate the probes specifically against the gravimetric method. An order-two polynomial function of the output period ( $\tau$ ) was adjusted against the gravimetric method by the least squares method, yielding  $\theta = 0.072\tau^2 + 0.361\tau - 0.298$ , with a relative RMSE of 8% for  $N = 20$ .

Soil heat storage was calculated for each layer ( $i$ ) as

$$G = \sum_{i=1}^{i=n} G_i = \sum_{i=1}^{i=n} C_i z_i \frac{dT_i}{dt} \quad (2)$$

where  $G$  is the soil heat storage ( $\text{W m}^{-2}$ ),  $C$  the volumetric heat capacity ( $\text{J m}^{-3} \text{K}^{-1}$ ),  $dT/dt$  the variation of temperature during period  $t$  ( $\text{K s}^{-1}$ ),  $z$  the thickness of the soil layer (m) and  $n$  is the number of soil layers. In order to calculate  $C$  of each soil layer, the specific heat value of each constituent (clay, silt + sand, organic matter, water and air) was multiplied by its respective density (values from Müller, 2000) and its volumetric fraction (values from Bonzon et al., 1991).

The variations of temperature in coconut stems was assessed on one coconut palm, using six  $0.2 \times 10^{-3}$  m copper-constantan TC leads, sealed in  $2 \times 10^{-3}$  m copper tubes and buried at breast height, just beyond the 'bark' surface, 1 cm under the 'bark' base and one in central stem, repeated for two azimuths, North and South. Leaflet temperature was assumed to be equal to the air temperature measured in the middle of the canopy. The air temperature profile was monitored using  $0.2 \times 10^{-3}$  m copper-constantan thermocouples leads shaded by foam/aluminium foil and placed at 0.2, 0.5, 1, 2, 4, 8, 12, 13, 15, 17 and 20 m using the reference temperature from a 10TCRT thermistance (Campbell Scientific, Shepshed, UK).

The pattern of heat storage in coconut palms and air was assumed to be the sum of  $J_v$  (heat storage in the vegetation),  $J_a$  (sensible heat storage in the air between the soil surface and the reference height) and  $J_w$  (latent heat storage in the same layer). In this formulation, the

photosynthetic storage ( $J_p$ ) was assumed to be negligible. The heat storage in the litter and the grass were not taken into consideration.

## 2.6. Sapflow

### 2.6.1. Calibration of the probes in the laboratory

Sapflow was measured by heat dissipation method (Granier, 1985, 1987; Lu et al., 2004) using home-made 20 mm-long radial probes, continuously heated (0.2 W), and connected to a data logger (CR10X and AM416 Multiplexer, Campbell Scientific, Shepshed, UK). In a preliminary approach, we used the default standard calibration parameters reported on a set of temperate species, Granier (1985):

$$F_g = \alpha K^\beta = 119 \times 10^{-6} \left[ \frac{\Delta T_0 - \Delta T_i}{\Delta T_i} \right]^{1.231} \quad (3)$$

where  $F_g$  ( $\text{m}(\text{H}_2\text{O})^3 \text{m}^{-2} \text{s}^{-1}$ ) is the sapflow density using standard (Granier, 1985, 1987) coefficients,  $\alpha$  ( $\text{m}(\text{H}_2\text{O})^3 \text{m}^{-2} \text{s}^{-1}$ ) and  $\beta$ ;  $K$  is the sapflow index calculated from  $\Delta T_0$  and  $\Delta T_i$ , the daily maximum and current temperature difference between the two sensors of the probe ( $^\circ\text{C}$ ), respectively.

The calibration of the home-made probes was checked in the laboratory with reference to the gravimetric method, using a 50 cm PVC pipe with an internal diameter of 4.1 cm, fully water tight and filled with compacted sawdust, as described by Granier (1985). Water flow was varied either by pressure during the descent of the water in the supply pipe (variable flow), or using a peristaltic pump (constant flow). Both reference methods yielded similar results and only results from the first one are reported here. The sapflow indices ( $K$ ) were much lower than expected from the adjusted relationship given by Granier (1985) (Fig. 1a). We checked that the power supply delivered the correct and constant output. The variability appeared reasonable from an assessment of eight probes and we adjusted parameters  $\alpha$  and  $\beta$  from Eq. (3), yielding  $\alpha = 315 \times 10^{-6} \text{m}(\text{H}_2\text{O})^3 \text{m}^{-2} \text{s}^{-1}$  and  $\beta$  close to the value obtained by Granier (1985) (Fig. 1b; Table 3). The intercept was close to zero and we checked that  $\beta$  could be fixed to the standard value of 1.231 ( $\alpha$  re-adjusted separately) without affecting the accuracy of the calibration ( $R^2 = 1.0$ ). Our probes were thus considered simply proportional to the ones of Granier.

### 2.6.2. Assessment of stand transpiration

In the field, the probes were inserted at breast height in the superficial and conductive part of stem, just beyond the 'bark'. Preliminary studies were dedicated to check

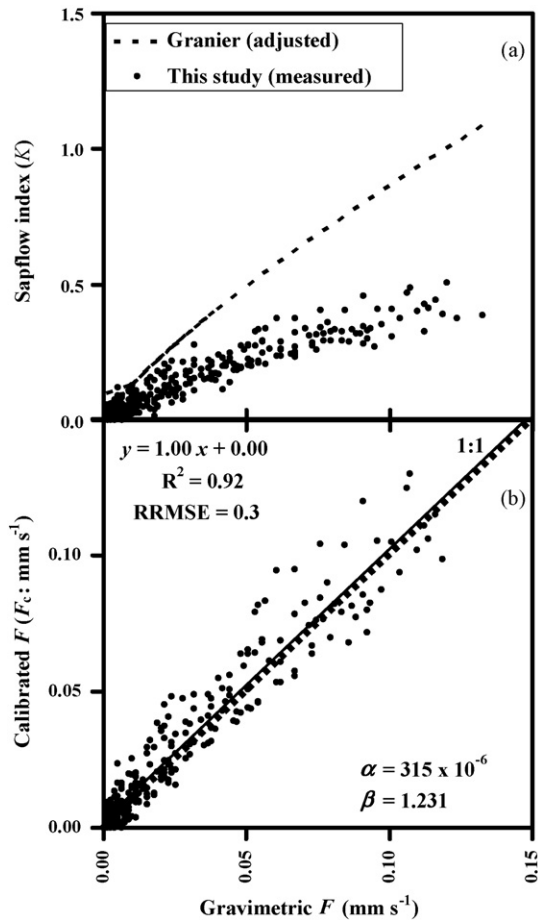


Fig. 1. Laboratory calibration of home-made sapflow probes against the gravimetric method: (a) sapflow index ( $K$ ) measured on home-made probes compared to original probes (Granier, adjusted); (b) calibrated sapflow density ( $F_c$ ) with adjusted coefficients  $\alpha$  and  $\beta$  for home-made probes.  $N = 8$  probes.  $F$ : sapflow density. RRMSE = relative root mean square error. The dotted line is the theoretical 1:1 relationship.

the reliability of sapflow measurements by this method in the coconut stem, checking for (i) natural thermal differences, (ii) radial distribution of sapflow, (iii) azimuthal variability and (iv) between-tree variability.

Natural thermal differences, if occurring, were often proved to affect sapflow computation considerably (Do and Rocheteau, 2002; Lundblad et al., 2001; Roupsard et al., 1999). Consequently they were evaluated here: they ranged only between  $-0.25$  and  $+0.03$  °C, i.e. 10 times less than the values obtained during the high transpiration rate. It was concluded that natural thermal differences could be neglected and no correction was applied.

Regarding the radial distribution of sapflow in the stem, preliminary staining experiments conducted with pressurised water in stem sections indicated that the

whole stem area was actually conductive. As described by Granier et al. (1996), radial sapflow was assessed on living palms using home-made 0.1 m-long sapflow probes, equipped each with four replications of 0.02 m-long heated portions, similarly to the standard sapflow probes. It was first checked that short and long sapflow probes yielded similar sapflow if both were recorded in the superficial part of the conductive stem at a similar azimuth. A normal (0.02 m long) sapflow probe was always used as a control in the superficial stem during every deep recording of sapflow with the long probe. Each part of the long sapflow probes was heated in succession, in order to avoid any thermal interaction. We found quite a constant pattern of sapflow density throughout the stem radius, up to 12 cm (Fig. 2). It was decided to extrapolate this simple constant pattern up to the stem centre point (about 15 cm deep), considering that its relative contribution would be negligible anyway.

The azimuthal variability of sapflow in coconut proved to be large, up to a factor of 3 between palms and was not predictable, probably due on the one hand to the position of the sun, affecting crown transpiration directionally and on the other hand to the heterogeneity of stem anatomy in the vicinity of the probe. Accordingly, a minimum of 10 coconut palms were monitored for sapflow (Table 1), five probes were directed to the South and five to the North.

Ten experimental palms were chosen as close as possible to the tower, in the footprint and at a maximum of 30 m upwind. The circumference at breast height is not an indicator of vigour in palms. Hence, sampling was made representative of a survey of stand height distribution (Table 1) and also the quantity of nuts per palm (by nut count, data not shown).

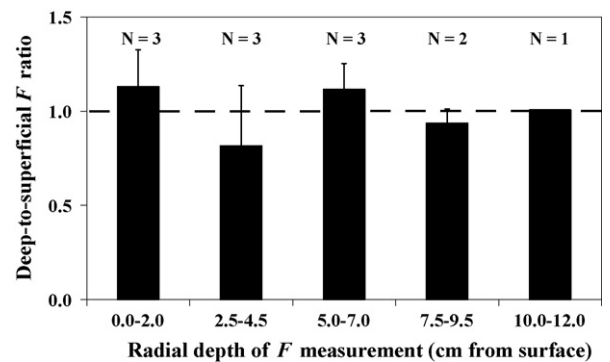


Fig. 2. Deep-to-superficial ratio of sapflow density ( $F$ ).  $F$  was measured deeply along the radius of the stem using a 10 cm-long probe equipped with four individual 2 cm-long probes heated in succession, up to 12 cm deep. Every deep  $F$  value was divided by surface  $F$  (0–2 cm), assessed by a reference short probe. Error bars indicate standard deviation.  $N$  = number of replicates.



We computed the stand transpiration,  $T$  as

$$T = D_p \frac{1}{n_p} \sum_{i=1}^{i=n_p} \sum_{j=1}^{j=n_r} (F_{i,j} A_{i,j}) \quad (4)$$

where  $T$  is the transpiration of the coconut palm layer of the stand ( $\text{mm h}^{-1}$ ),  $D_p$  the coconut palm density ( $\text{tree ha}^{-1}$ ),  $F$  the sapflow density,  $A$  the conductive area of stem ring,  $n_p$  the number of sampled coconut palms and  $n_r$  is the number of rings.

### 2.7. Cross-validation of sapflow and eddy-covariance

A calibration of sapflow was attempted in the field following:

$$E - E_u = T + I \quad (5)$$

where  $E$  is the evapo-transpiration of the stand,  $E_u$  the evapo-transpiration of the under-storey,  $T$  the transpiration of the coconut palms and  $I$  is the rainfall interception by the cover, all expressed in  $\text{mm h}^{-1}$ .

Two experiments for measuring fluxes above (22 m) and below the coconut canopy (5.5 m) were planned: experiment 1 (warm season, from the 28 January to the 13 February 2002, sun elevation close to vertical at zenith) and experiment 2 in contrasting conditions (cool season from the 20 May to the 12 June 2002, low solar elevation). We used two sonic anemometers (Gill WindMaster Pro and Young 8100) and one Li-7500. The sonic anemometers were first cross-calibrated at reference height ( $R^2 = 0.99$ ). We checked for the correct energy balance closure when every instrument was placed at reference height. We determined  $a$  and  $b$ , the slope and intercepts of the following relationship:

$$H + \lambda E + G + Q = aR_n + b \quad (6)$$

When the Gill sonic and Li-7500 were displaced below the canopy for measuring  $H_u$  and  $\lambda E_u$ , we used Eq. (6) to estimate  $\lambda E$  at reference height, with  $a$  and  $b$  calibrated just before the experiment 1 or 2.

During experiment 1, we calibrated the coefficients  $\alpha$  and  $\beta$  of Eq. (3) by least squares method in order to match  $T$  and  $E - E_u$  in conditions when the cover was dry ( $I = 0$ ). It was required that these coefficients would be specific to the coconut stem and not sensitive to the relative evaporation of the under-storey, which might vary across seasons, following superficial soil water availability or solar elevation for example. Hence, the calibration of experiment 1 was checked for validation during contrasting conditions (experiment 2).

Table 2  
Data set statistics on a half-hourly time-step

	Rain = 0	Climate	$H$	$\lambda E$	$T$	$G$	$J$
Mean % of data retained	89	98	76	71	73	40	52
CV (%)	3	1	7	4	27	13	21

Percentage of data retained after quality checking. The 3-year data set of half-hourly values was split into 6-month fractions. Mean and coefficient of variation (CV) of the six fractions. First column (rain = 0) indicates the percentage of non-rainy half-hours. The climate column represents all radiation, temperature and humidity values, measured at reference height (22 m) above the canopy.

### 2.8. Quality checking, data filtering and gap-filling

We found no trend at all in the energy balance closure, with respect to either wind direction or windspeed (data not shown), indicating that the data set did not need to be split by wind classes. Ninety eight percent of the climate data were collected. The proportion of missing data is given in Table 2, showing the means of 6-month pools of data. On a half-hourly time step,  $R_n$  displayed very few gaps or inconsistencies. Short gaps (<2 h) were filled by linear interpolation, and longer ones estimated from the linear relationship ( $R^2 = 0.97$ ) obtained between measured  $R_n$  and the  $R_n$  model proposed by FAO (1998), where  $R_n$  is derived from downward global radiation, clear-sky solar radiation, albedo, air temperature and vapour pressure.

Spikes in the signal of  $H$  and  $\lambda E$  that have occurred were mainly due to electrical problems and few to rain events. The signals were despiked in accordance with variance filters and if excessive variance was noticed in the relationship with  $R_n$ . Only around 73% of  $H$  and  $\lambda E$  remained after the despiking and filtering processes. However, the spikes proved to be randomly distributed.  $H$  was gap-filled using observed linear relationships with  $R_n$ , updated every month ( $R^2 > 0.95$ ). The missing values of  $\lambda E$  (around 29%) were estimated from monthly adjustments of  $a$  and  $b$  in Eq. (6) ( $R^2 > 0.95$ ). Seventy three percent of  $T$  values were recovered, filtered similarly to  $H$  and gap-filled at monthly time-scale using mean diurnal variation (MDV).  $G$  and  $Q_a$ ,  $Q_v$ ,  $Q_w$  displayed the largest gaps, due to instrument breakdowns and spikes and were gap-filled with MDV.

## 3. Results

### 3.1. Climate and plant water status

The seasonal trends in climate and soil water availability are shown in Fig. 3, showing distinctly the

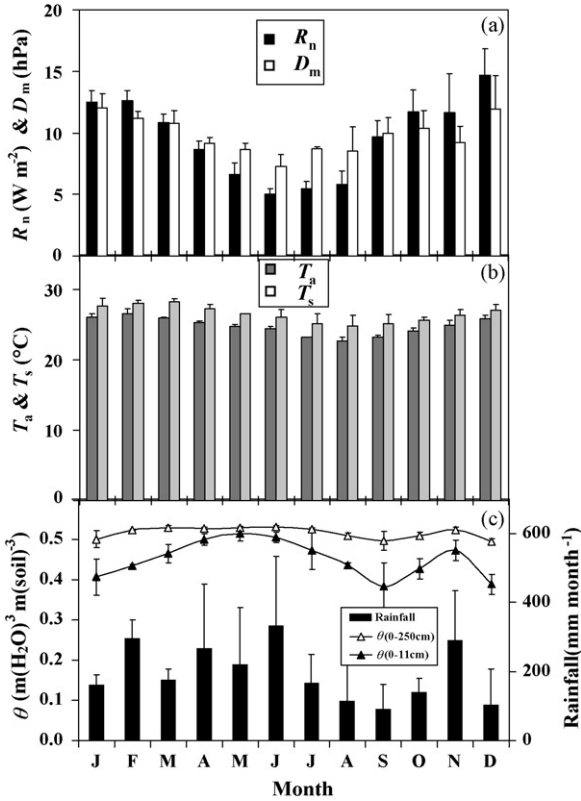


Fig. 3. Seasonal trends for climate and soil water content: (a) net radiation ( $R_n$ ) and daily maximum vapour pressure deficit ( $D_m$ ); (b) air temperature ( $T_a$ ; reference height, 22 m) and soil temperature ( $T_s$ ; -2 cm); (c) rainfall and soil volumetric water content ( $\theta$ ) of top-layer (0–11 cm) and of total soil profile (0–250 cm). Each symbol is a monthly average or monthly sum  $\pm$  standard deviation (error bars) for 3 years of measurements.

warm/wet and cool seasons. Net radiation varied seasonally by a factor of 3 (Fig. 3a). It led to variations in vapour pressure deficit (VPD,  $D$ ), the daily maximum values of which ( $D_m$ ) did not peak beyond 12 h Pa. The annual variations of air and soil temperatures remained within 4 °C (Fig. 3b). Total rainfall was 2360  $\text{mm year}^{-1}$  over that period (Fig. 3c). Soil volumetric water content ( $\theta$ ) remained above 0.38  $\text{m}(\text{H}_2\text{O})^3 \text{m}(\text{soil})^{-3}$  when considering only the surface layer and above 0.49  $\text{m}(\text{H}_2\text{O})^3 \text{m}(\text{soil})^{-3}$  when considering the total soil profile. These recordings indicate that the seasonality was driven by radiation, VPD and rainfall. Excepted in the surface layers where the soil could exceptionally dry out, the soil profile remained close to field capacity.

### 3.2. Leaf area index

From destructive sampling of 10 trees, we found that the dry mass of leaflets per leaf ( $M_l$ ; kg) could be related

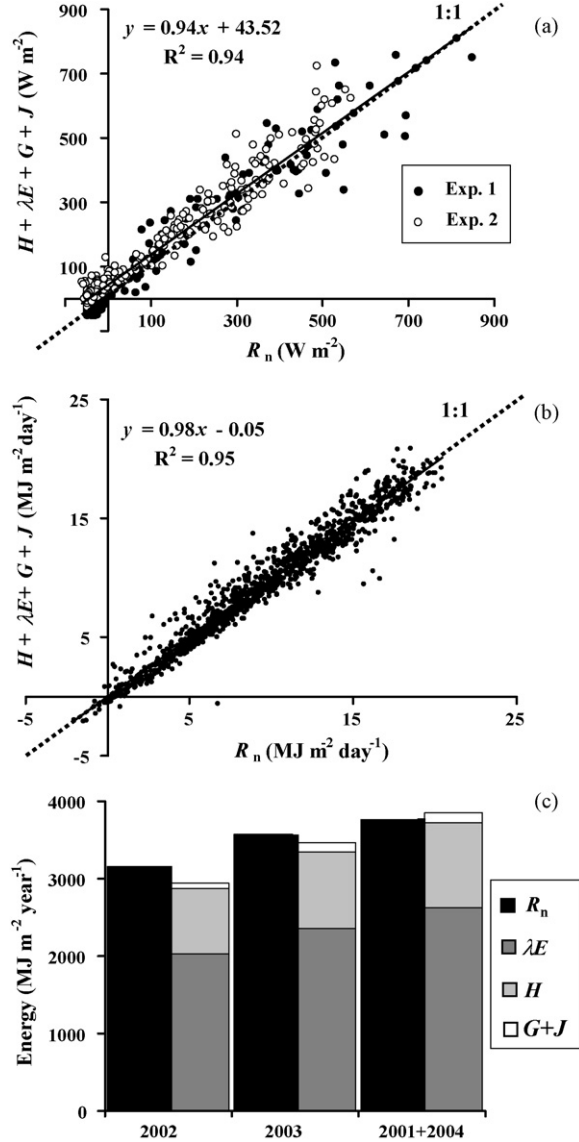


Fig. 4. Energy balance closure of the stand: (a) on a half-hourly time step for experiment 1 (warm season) and experiment 2 (cool season); (b) on a daily time step for 3 years; (c) on a yearly time step.  $R_n$ : net radiation;  $H$ : sensible heat flux;  $\lambda E$ : latent heat flux;  $G$ : soil heat storage (0–100 cm);  $J$ : air, vapour, stem and leaf heat storage. The dotted line is the theoretical 1:1 relationship.

empirically to the leaf rank ( $R_l$ :  $R_l = 1$  for the newly emitted leaf at top of and incrementing towards bottom of crown):  $M_l = -8.47 \times 10^{-6} R_l^4 + 5.85 \times 10^{-4} R_l^3 - 1.53 \times 10^{-2} R_l^2 + 1.69 \times 10^{-1} R_l + 8.13 \times 10^{-1}$ ;  $R^2 = 0.73$ ;  $N = 66$  leaves. The leaf dry mass-to-area ratio or LMA ( $l_p$ ;  $\text{kg m}^{-2}$ ) was found rather constant for every leaflet of a leaf, but variable relatively to  $R_l$ :  $l_p = 1.39 \times 10^{-3} R_l + 182.72 \times 10^{-3}$ ;  $R^2 = 0.84$ ;  $N = 104$  leaflets. We calculated that leaf area index,  $L_p$  was

$2.95 \text{ m(leaf)}^2 \text{ m(soil)}^{-2}$ , i.e.  $\approx 3$ . After monitoring the number of leaves on 10 trees, we found that it did not change by more than  $32 \pm 1$  leaf between the contrasting warm and cool seasons (Table 1). LAI of coconut palm was thus considered constant throughout the experiment. The leaf emission period was 28 days, indicating that leaf lifespan (from emergence to shedding) was around 30 months. The soil coverage index (estimated by vertical projection of the coconut canopy) was estimated around 75%. The leaf area of the grass under-storey ( $L_u$ ), was constant in the litter inter-row and the row (both not slashed, covering 51% of the total area) and varied between a minimum and a maximum value in the clear inter-row (grass slashed every 2 months, covering 49% of total area). The mean value of 2.7 for  $L_u$  was quite similar to  $L_p$ .

### 3.3. Reliability of latent heat flux measurements above the canopy ( $\lambda E$ )

#### 3.3.1. Energy balance closure

Energy balance closure ( $H$  and  $\lambda E$  measured above the canopy) was satisfactorily achieved on a half-hourly time step during experiment 1 (warm season) and experiment 2 (cool season) (Fig. 4a). The sum  $H + \lambda E + G + J$  explained 94% of the variability of

the net radiation ( $R_n$ ), with a slope of 0.94 and an intercept of  $44 \text{ W m}^{-2}$ .

On a daily time-step, the energy balance closure was 98% of  $R_n$ ;  $R^2 = 0.95$ ;  $N = 1095$  days (Fig. 4b). Fig. 4c shows the cumulated energy balance closure for each of the 2 years, which was 93% of  $R_n$  with little inter-annual variation (year 3 was re-composed using available monthly values from 2001 and 2004). The yearly sum of  $G + J$  was negligible but not zero, as would be normally expected. We observed that under our conditions, the zero-plane for soil thermal changes was probably more than 1 m and that some  $G$  fluxes beyond might have been un-accounted for.

#### 3.3.2. Spectral analysis

The spectral density ( $S$ ) on the y-axis was multiplied by the natural frequency ( $n$ ) and normalised by the variance (spectra), or covariance (co-spectra) (Fig. 5). The natural frequency was represented on the x-axis. The spectra above the canopy (Fig. 5a) displayed broad peaks in the frequency range between 0.01 and 0.1 Hz. A drop-off was observed at higher frequencies. Its slope was close to  $-2/3$ . The co-spectra  $w'T'$  and  $w'q'$  overlaid each other (Fig. 5c), indicating that sources emanated from the same location. The slope of the drop-off in co-spectra was close to  $-4/3$ . Below the

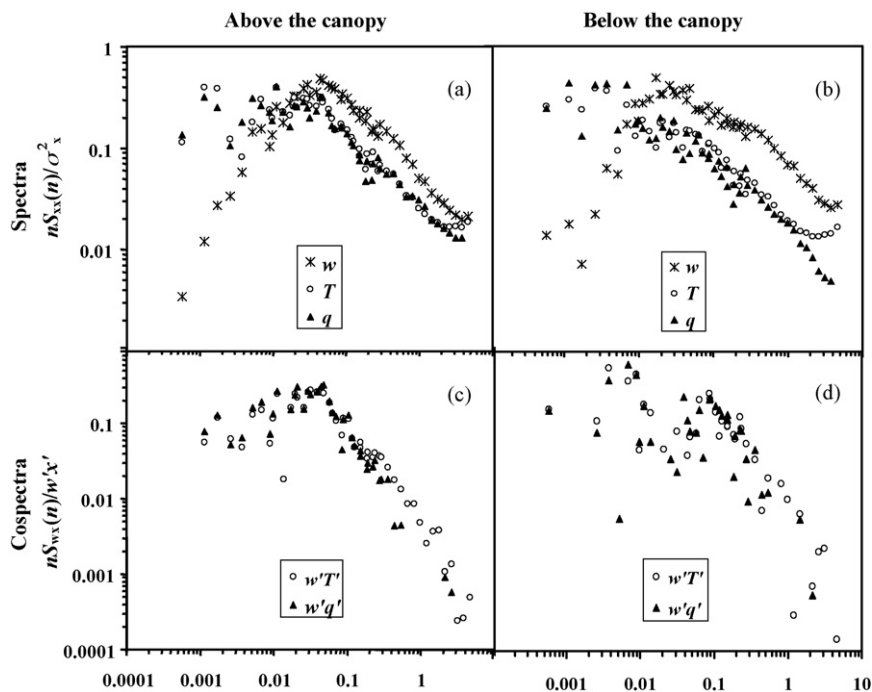


Fig. 5. Examples of spectral analysis above (22 m) and below (5.5 m) the canopy: (a) spectra for vertical wind velocity ( $w$ ), temperature ( $T$ ) and humidity ( $q$ ) above the canopy; (b) ditto below the canopy; (c) co-spectra of  $w'T'$  and  $w'q'$  above the canopy; (d) ditto below the canopy. Each dot is an average from three half-hourly samples, chosen at similar wind-speeds and close to stability.

canopy (Fig. 5b and d), results were quite similar. Spectral peaks occurred at similar natural frequency above and below the canopy.

### 3.4. Sapflow and canopy transpiration in the field

Palm transpiration derived from sapflow and computed using standard calibration coefficients ( $T_g$ ) was well correlated with stand evapo-transpiration measured by eddy-covariance ( $E$ ) during experiments 1 and 2 (Fig. 6a). The best fit was obtained without introducing any time-lag between  $E$  and  $T$ . The correlation coefficients ( $R^2$ ) for the linear

correlation were over 0.83, and intercepts were close to zero (Fig. 6a and details in Table 3). However, the average slope was 3.73, which was unexpectedly high, considering that the LAI of the coconut palms was  $\approx 3$  and coconut canopies were covering around 75% of the soil. It was confirmed that the sapflow system, although correlated with  $E$  required a specific calibration.

Coconut canopy transpiration was computed as the difference between stand ( $E$ ) and under-storey evapo-transpiration ( $E_u$ ), selecting conditions when rainfall interception was nil. During experiment 1 (warm season),  $E - E_u$  was used for calibrating the sapflow coefficients  $\alpha$  and  $\beta$  in the field, resulting in a calibrated transpiration,  $T_c$  (Fig. 6b). Using the same coefficients during experiment 2 for validation in conditions of contrasting climate conditions, we found that the slope was unity and the intercept close to zero. Hence,  $T$  from Eq. (4) was calibrated by  $E - E_u$  after pooling both experiments and optimising the coefficients  $\alpha$  and  $\beta$  of Eq. (3) (Table 3). The values  $\alpha = 339 \times 10^{-6} \text{ m}(\text{H}_2\text{O})^3 \text{ m}^{-2} \text{ s}^{-1}$  and  $\beta = 1.23$  were derived.  $\beta$  was very close to the value proposed by Granier (1985).

The sapflow coefficients calibrated in the field confirmed the ones obtained in the laboratory (Table 3). This resulted in a general validation of measured  $E_u$  by  $E - T$ , where  $E$  was validated independently through energy balance closure above the canopy and  $T$  through successful comparison of laboratory and field coefficients.

### 3.5. Seasonal and inter-annual variations

The seasonal variability of the partitioning is shown in Fig. 7. The data corresponded to monthly averages of daily energy fluxes after gap-filling (Fig. 7a). The 3 years of monitoring were pooled together so that the standard deviations represented the inter-annual variability, which proved to be moderate or small.  $R_n$  decreased by a factor of three between the warm and cool seasons, due to the elevation of the sun, the photoperiod and cloud cover. Warming and cooling periods were detected in the time course of  $G$  and  $J$ , consistently with radiation. Taken yearly,  $H$  represented about 26% of  $R_n$  and the Bowen ratio ( $H/\lambda E$ ) was low (0.39), which was clearly indicating a large evapo-transpiration and confirming a large soil water availability. The Bowen ratio varied significantly seasonally, though, from 0.16 (July) up to 0.59 (December), indicating a limitation of evapo-transpiration during the warm season. The partitioning of energy remained very similar for each year (Fig. 4c).

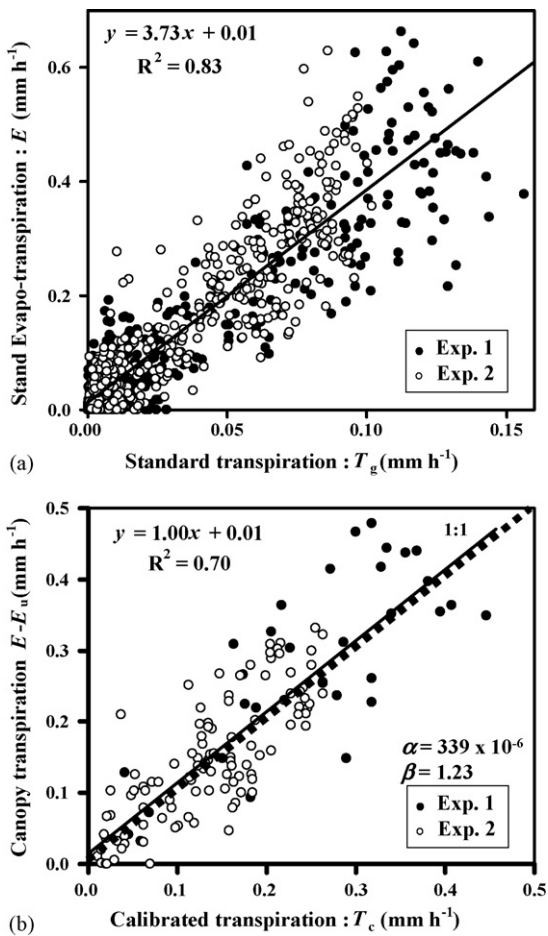


Fig. 6. Field calibration of the sapflow probes: (a) relationship between stand evapo-transpiration measured by eddy-covariance ( $E$ ) and coconut palm transpiration ( $T_g$ ) using the standard (Granier) sapflow coefficients  $\alpha$  and  $\beta$ ; (b) relationship between the field-calibrated transpiration ( $T_c$ ) and  $E - E_u$  (canopy transpiration) where experiment 1 (warm season) was used for calibration of sapflow coefficients  $\alpha$  and  $\beta$  and experiment 2 (cool season) for validation of the same coefficients. Each point is a half-hourly value. The dotted line is the theoretical 1:1 relationship.

Table 3  
Calibration of sapflow in the laboratory and cross-validation in the field

Description	Field experiment 1 (warm conditions)	Field experiment 2 (cool conditions)	General calibration
Dates of experiments above & below the canopy (2002)	28 January–4 February and 5–13 February	20–23 May + 5–12 June and 24 May–4 June	–
Mean soil volumetric water content, $\theta_{0-11 \text{ cm}}$ ( $\text{m}(\text{H}_2\text{O})^3 \text{ m}(\text{soil})^{-3}$ )	0.45	0.55	–
Maximum net radiation, $R_n$ ( $\text{W m}^{-2}$ )	792	564	–
Calibration of standard probes (Granier, 1985)	–	–	$\alpha = 119 \times 10^{-6}$ and $\beta = 1.231$
Calibration of home-made probes in the laboratory	–	–	$\alpha = 315 \times 10^{-6}$ and $\beta = 1.23$
Relationship between $E$ and $T_g$ ( $T$ using Granier standard coefficients)	$E = 3.49 T_g + 0.01$ ; $R^2 = 0.84$	$E = 4.1 T_g + 0.01$ ; $R^2 = 0.83$	$E = 3.73 T_g + 0.01$ ; $R^2 = 0.83$
Final calibration of $T_c$ ( $T$ with field-adjusted coefficients)	$E - E_u = 1.00 T_c + 0.03$ ; $R^2 = 0.59$ ; $\alpha = 318 \times 10^{-6}$ ; $\beta = 1.20$	$E - E_u = 1.00 T_c + 0.01$ ; $R^2 = 0.63$ ; $\alpha = 317 \times 10^{-6}$ ; $\beta = 1.20$	$E - E_u = 1.00 T_c + 0.01$ ; $R^2 = 0.70$ ; $\alpha = 339 \times 10^{-6}$ ; $\beta = 1.23$

$E$ : stand evapo-transpiration;  $E_u$ : evapo-transpiration of the under-storey;  $E - E_u$ : canopy transpiration;  $T_g$ : measured sapflow using the standard calibration coefficients (Granier, 1985);  $T_c$ : calibrated sapflow with adjusted coefficients.  $\alpha$  and  $\beta$ : calibration coefficients for heat-dissipative probes.

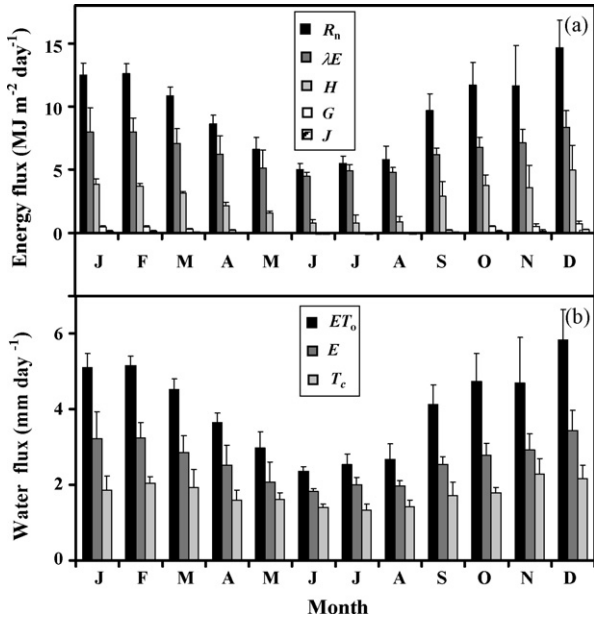


Fig. 7. Seasonal (monthly) trends of partitioning of stand energy balance and evapo-transpiration terms, all averaged over 3 years. (a) Energy balance terms: net radiation ( $R_n$ ), sensible heat flux ( $H$ ), latent heat flux ( $\lambda E$ ), soil heat flux ( $G$ ) and stand heat storage ( $J$ ); (b) evapo-transpiration terms: Penman–Monteith potential evapo-transpiration ( $ET_o$ ), stand evapo-transpiration ( $E$ ), and palm transpiration assessed by sapflow ( $T$ ). One bar is the mean daily value for each month  $\pm$  standard deviation (error bars).

The seasonal variations of the potential evapo-transpiration of a theoretical wet grass ( $ET_o$ ), of measured evapo-transpiration ( $E$ ) and of its partitioning into palm transpiration ( $T$ ) are shown in Fig. 7b.  $E$  was around  $952 \text{ mm year}^{-1}$  that is only 40% of rainfall and varied seasonally between 16 and 100% of rainfall.  $E$  varied seasonally between 59 and 79% of  $ET_o$ , with a yearly average at 67%. These values corresponded to the fluctuations in the crop coefficient,  $K_c = E/ET_o$ , as defined in FAO (1998).

$T$  was around  $642 \text{ mm year}^{-1}$ , and ranged monthly between 1.3 and  $2.3 \text{ mm day}^{-1}$ , i.e. between 93 and  $160 \text{ kg}(\text{H}_2\text{O}) \text{ palm}^{-1} \text{ day}^{-1}$ .  $T$  amounted to around 68% of  $E$ .  $T$  was not much influenced by the seasonality as compared to  $E$ , which will be discussed further in terms of stomatal limitation. The difference between  $E$  and  $T$ , which could be attributed to  $E_u + I$ , appeared to be much reduced during low sun elevation periods. We found no significant correlation at all between the soil volumetric water content (in surface or for the total profile) and  $T$  or  $E - T$ .

#### 4. Discussion

Although Wilson and Meyers (2001) consider that the errors associated to the measurement of water vapour flux below the canopy,  $E_u$  are expected to be of the order of 10%, we considered that apparent  $E_u$  could



be biased by structural (open or close canopy) and turbulence conditions. Similarly, sapflow could be biased by probe calibration and stem anatomy problems. Using a combination of approaches and methodologies together supports the overall reliability of the measurements and water budgets. An independent validation of evapo-transpiration of the stand ( $E$ ) through energy balance closure and of ( $T$ ) through laboratory and field comparisons was expected to yield the required cross-validation of  $E_u$  by  $E - T$ .

#### 4.1. Reliability of turbulent energy fluxes above and below the canopy

Above the canopy, the sensible ( $H$ ) and latent ( $\lambda E$ ) heat fluxes could be considered reliable, given the satisfactory correlation observed with available energy ( $R_n - G - J$ ) at various time steps. Below the canopy, the energy balance closure method often fails to assess the reliability of fluxes. In their attempt of measuring and modelling energy fluxes above the floor of two coniferous forests, Baldocchi et al. (2000) concluded that significant amounts of horizontal advection of energy within the sub-canopy air space were driven by large radiation gradients below the canopy, leading to sampling errors. In their study, only 71% of the variance of  $R_n$  was described by  $H + \lambda E + G$ , with a slope of 0.88, which is not in favour of the energy balance closure approach to our understanding.

We found here that most characteristics of spectra and co-spectra remained quite similar above and below the canopy. Interestingly, the spectral peaks occurred at similar natural frequency above and below the canopy despite large differences in measurement height, displacement height (estimated at 0 for the short vegetation of the under-storey) and wind-speed: this is indicating that the turbulence above the canopy was driving the one below the canopy. Results are consistent with an open canopy structure. The slope of the drop-off was close to  $-2/3$  for spectra, indicating that the behaviour was similar to surface boundary layer turbulence (e.g. Kaimal et al., 1972). The slope in co-spectra was close to  $-4/3$ , consistently with theory (Kaimal and Finnigan, 1994). We concluded that we measured most of the turbulent eddies that contributed to turbulence variance and co-variance. Other authors find slopes in co-spectra ranging between  $-3/4$  and  $-4/3$ , or else an intermediary slope close to  $-1$  (Amiro, 1990; Baldocchi and Hutchinson, 1987).

However, some questions persist below the canopy, including issues relating to the stationarity of the canopy environment, energy balance closure, instrument placement, sensor separation, averaging time and

filtering time constants. As a whole, the reliability of turbulent energy fluxes below the canopy required cross-validation with independent methods.

#### 4.2. Reliability of sapflow

Many reports show good agreement between thermal dissipation and other methods for assessing transpiration in a large set of species (e.g. maritime pine, Berbigier et al., 1996; beech, Köstner et al., 1992 or Granier et al., 2000; aspen, Hogg et al., 1997; jack pine, Saugier et al., 1997).

In the present study on coconut palms, instantaneous and daily tracking of  $E$  and  $T$  yielded consistent trends in the absence of interception events, similarly to the conclusions of Wilson et al. (2001). However, sapflow appeared to be under-estimated by a factor of 3. After monitoring eddy-covariance and sapflow in a mixed deciduous forest of uneven ages, Wilson et al. (2001) reported that sapflow was only 50% of  $E$ , which they also considered un-realistic, after comparing this to their measurement of  $E - E_u$ . In their study,  $E$  converged with independent measurements of catchment water budgets, the energy balance closure was reasonable and the measurement of soil evaporation could not fill their apparent gap between  $E - E_u - I$  and  $T$ . They were using commercial 30 mm-long gauges with the heating element contained in a cylindrical housing (contrary to gauge described in Granier, 1985) and they stressed the fact that differences in construction might affect the calibration coefficients. Some large discrepancies (up to a factor of 5) affecting the heat dissipation method with respect to reference methods have been reported too, e.g. by comparing heat balance (Cermák et al., 1973, an absolute method, used here as a reference) and heat dissipation (Granier, 1985) in pine and spruce (Lundblad et al., 2001), or in spruce (Offenthaler et al., 1998). The non-active area in contact with the probe might largely affect its sensitivity (Clearwater et al., 1999). This is a crucial problem for long term sapflow monitoring in trees with annual growth rings, since calibration might vary with time. In monocots, there is no radial growth and it can be assumed that the calibration coefficients are fixed over time. However, they are expected to vary in accordance with the probe position, and only extensive tree sampling can account for the expected variability.

Given the multiple sources of bias associated with sapflow probes, we checked (i) that natural thermal differences could be overlooked, (ii) that nocturnal transpiration was close to zero, as inferred from steady values of soil water content and from high air humidity values at night, and (iii) that radial distribution of sapflow

was properly taken into account. We concluded that the discrepancy between  $T$  and  $E - E_u$  was likely to originate either from probe calibration or coconut stem anatomy. The value we found for sapflow coefficient  $\alpha$  was comparable for laboratory and field calibrations and the value of  $\beta$  was always close to the standard so our recalibration was just a slope shift. Additionally, our field calibration was not influenced by contrasting climatic conditions. We consider that probe calibration issues explained most of the apparent discrepancy between  $T$  and  $E - E_u$ . Since  $E$  was also reliable (energy balance closure) and spectral results confirmed theory above and below the canopy, we argue here that our experiments allowed to cross-validate independent eddy-correlation and sapflow results. This is an important result that is supporting the use of heat-dissipative probes in other palm species and the measurement of  $E_u$  in open canopies.

Supporting Wilson et al. (2001), we stress the fact that these sapflow results are likely dependent on the exact type of gauge being used, and that they should possibly be checked before using different gauges. Wherever possible, it is recommended to re-calibrate the measuring system (gauge + power supply) against the gravimetric method, on cut portions from the species itself and in the laboratory.

The maximum values for instantaneous sapflow densities ( $F_c$  from Eq. (3), after re-calibration using field coefficients) recorded on all 10 gauges ranged between 2 and 6  $\text{kg}(\text{H}_2\text{O}) \text{ dm}^{-2} \text{ h}^{-1}$ , with an average of 3.5  $\text{kg}(\text{H}_2\text{O}) \text{ dm}^{-2} \text{ h}^{-1}$  during the warm season (greatest transpiration). This average value close to the maximum values of 1–4  $\text{kg}(\text{H}_2\text{O}) \text{ dm}^{-2} \text{ h}^{-1}$  reported by Granier et al. (1996) on a set of tropical rainforest species, 1.5 times more than on a phreatophytic species, *Faidherbia albida* subjected to high  $ET_o$  (Roupsard et al., 1999) and 2.3 times more than on a temperate oak (*Quercus petraea*).

On a half-hourly time-step, we found that the best fit between  $E$  and  $T$  was obtained without introducing any time-lag. In other species, the time-lag of  $T$  is variable, depending on the species but also on instantaneous evaporation rates (Saugier et al., 1997) and can reach up to 1.5 h (Granier et al., 1996). Our result might indicate that water exchange with the stem itself (charge and discharge) was not great in relation with the evaporative demand. On isolated agroforestry trees, Roupsard et al. (1999) found that sapflow even preceded the onset of atmospheric demand in the morning, and attributed it to the early radiation interception by the crown. Similar effects can explain the absence of time-lag in row-planted palms, such as coconuts.

#### 4.3. Soil water and plant water status

Since  $E$  was about 50% of rainfall, it was likely that soil water drainage was of the same magnitude. We did not measure the drainage. In such conditions, the soil water balance method is not expected to yield realistic results of evapo-transpiration. Cuenca et al. (1997) and Moore et al. (2000) reported that soil water balance estimates were about 60% less than eddy-covariance by the end Jack Pine growing season, although they carefully accounted for drainage concerns. Dufrene et al. (1992) similarly could not estimate evapo-transpiration from the soil water balance for most of the oil palm wet season.

Coconut palm roots extended till the bottom of the soil profile (2.50 m) or even beyond and were likely to equilibrate overnight with close-to-optimum water potentials. The high values observed for soil moisture were consistent with the report of Bonzon et al. (1991) on the same stand. They reported that soil water content ranged from 0.35 at wilting point to 0.5  $\text{kg}(\text{H}_2\text{O}) \text{ kg}(\text{soil})^{-1}$  at field capacity, so extractable water was around 15%. It was attributed to high clay contents (over 80%). We could not find any relationship between transpiration and soil moisture, even when considering surface layers. The coconut roots reached the limestone (observed from trenching experiments), and eventually penetrated through it. The maximum VPD remained moderate as well. Given all these pedo-climatic features, it was unlikely that coconut palms experienced drought during the experiment. Taking a soil depth of 2.5 m, a threshold for stomatal closure in response to soil water availability of 0.5 times the extractable water, the soil water reserve would be around 200 mm before the beginning of drought symptoms. Given the yearly mean evaporation rate of 2.6  $\text{mm day}^{-1}$ , the buffer would be sufficient for about 70 days without rain, which never occurs, excepted during El-Niño events.

#### 4.4. Eco-physiology of coconut plantations

The evapo-transpiration of the coconut stand ( $E$ ) ranged seasonally between 1.8 and 3.4  $\text{mm day}^{-1}$ ,  $ET_o$  (FAO, Penman–Monteith) between 2.4 and 5.8 mm, and the crop coefficient,  $K_c$ , between 0.79 and 0.59 during the cool and warm seasons, respectively. These results confirm some other reports on palms. In Kerala (India), Jayakumar et al. (1988) measured the evapo-transpiration of 6-year-old coconut palms ( $L_p = 2.4$ ; stem density = 200) in the field by lysimetry (with soil maintained at field capacity) during the dry period and under conditions where atmospheric demand was

maximum. They reported that  $E$  ranged from 2.8 to 3.6 mm day<sup>-1</sup>,  $ET_{\text{Penman}}$  from 4.9 to 6.9 mm day<sup>-1</sup> and the corresponding  $K_c$  from 0.57 to 0.48. Both methods thus corroborate pretty well. On oil palm in Ivory Coast, Dufrene et al. (1992) reported that  $K_c$  ranged similarly between 0.81 (wet season) and 0.56 (dry season), the major difference being LAI (4–5.6 for oil palm). In temperate forests,  $K_c$  ranges currently between 0.64 (Aussenac and Boulangeat, 1980) and more than 0.8. In tropical forests, Huttel (1975) reported the value of 0.71.

It is questionable why  $K_c$  was reduced and why the Bowen ratio was increased during warm periods, despite a constant LAI and close-to-optimum soil water availability. Using Fick's law, we computed the ratio between daily integrated  $T$  and mean daily VPD ( $T/D$ ) as a simple daily integrated surrogate for canopy conductance ( $g_c$ ). The slope of the relationship between  $g_c$  and photosynthetic photon flux density (PAR:  $Q_p$ ) decreased much as VPD increased (data not shown) indicating that  $g_c$  was affected by VPD. We found in coconut palm that the value of  $g_c$  ranged from 2.5 to 18 mm s<sup>-1</sup>, that is, converted into equivalent leaf stomatal resistance using LAI = 2.95, equivalent to 0.17–1.2 s mm<sup>-1</sup>. In Kerala, Kasturibai et al. (1988) suggested also that coconut stomatal resistance was very sensitive to VPD, increasing sharply from 0.3 to 0.8 s mm<sup>-1</sup> between 10:00 and 12:00 a.m. during the dry season in rainfed (dry) conditions. The evapo-transpiration was hardly higher in Kerala than in Vanuatu despite a much larger potential evapo-transpiration and  $K_c$  was consequently much lower in Kerala. In oil palm however, Dufrene et al. (1992) reported that the daily stomatal conductance was two times less than in the present study, ranging between 0.1 and 10 mm s<sup>-1</sup>. They also reported a sharp sensitivity to VPD:  $g_{\text{max}}$  decreased by 50% when VPD increased from 1 to 1.8 kPa. The high sensitivity of  $g_c$  to VPD might be a common trait of canopies in humid tropics.

Regarding the partitioning of water vapour fluxes, the seasonal variability for  $T$  was less than for  $E$ .  $T/E$  decreased by 25% during the warm and high VPD period, due on the one hand to more energy available for the under-storey and on the other hand to stomatal closure in the coconut canopy.

Yearly,  $T$  amounted to 68% of  $E$ . Similarly, in a tropical forest, Shuttleworth et al. (1984) reported a  $T/E$  of 0.68. In oil palm in Ivory Coast (Dufrene et al., 1992), when the soil was close to field capacity,  $T$  (Penman–Monteith with a stomatal monitoring) amounted to 89% of  $E$  (soil water balance). A larger  $T/E$  in oil palm was consistent with its larger LAI.

It turns that our results for water flux partitioning were quite realistic when compared to similar ecosystems or plants. The most striking result is that energy and water fluxes appeared to track the elevation of the sun and radiation over the whole year, indicating that this tropical ecosystem is remarkably simple and predictable. The only drawback would be the impact of VPD on stomatal regulation.

## 5. Conclusions and perspectives

This monitoring of energy and water fluxes above and within a coconut plantation showed that even under close-to-optimum conditions (no nutritional or water stress, continuous growth, constant LAI), substantial seasonal variations occurred in the partitioning of available energy. The variations were mostly due to radiation. Nevertheless, the potential variations in canopy transpiration were dampened by stomatal closure during the warm seasons that also displayed a higher VPD. The time-course of coconut palm transpiration appeared much smoothed when compared to stand evapo-transpiration and to potential evapo-transpiration.

Plant and ecosystem eco-physiology are usually severely complicated in temperate regions by seasonal climate variations, drought and cold limitations. Given its apparent simplicity, this kind of ecosystem and this kind of plant offer exciting challenges for further testing critical assumptions about the physiology of perennial plants, such as reserve storage and dynamics (Mialet-Serra et al., 2005), competition for resources and agroforestry (Dauzat and Eroy, 1997). We claim that tropical palms are very promising plant models for investigating the functional ecology of perennial crops and forest trees.

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