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DETERMINATION OF THE ENERGY EXCHANGES OF A FOREST-TYPE CULTURE: HEVEA BRASILIENSIS

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ABSTRACT

The energy exchanges from a 23.5 m high rubber stand located in the tropical rain forest of Ivory Coast were determined using the energy balance-Bowen ratio method. The analysis shows that during the vegetative growing period (11 months) the radiation budget is nearly constant: it represents 72% of the global radiation. The distribution of available energy between latent and sensible heat depends on the leaf age, the air water vapour pressure deficit and the soil water availability. The amount of water vapour released in the atmosphere by the rubber forest represents 3 to 5 mm day^{-1} during nine months of the vegetative period and 1 to 3 mm day^{-1} two months before the leaf fall. Fluctuations of the canopy photosynthetic capacity are also dependent on soil water availability and leaf age.

INTRODUCTION

It is commonly accepted that humid tropical regions have a high radiation income and abundant precipitation so that the air is very humid and hot. It is easy to conclude that these climatic conditions generate exuberant tropical vegetation. However, this is a very misleading idea. Seasonal changes in climate may be considerable in west Africa due to the shift of the Intertropical Convergence Zone which separates two air masses with different characteristics. The alternation of the Intertropical Convergence Zone (ITCZ) determines the climate and the occurrence of the dry and rainy seasons. The tropical forest is subjected to 2 to 4 months of dry season with a period of a few weeks when a drier

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wind, the Harmattan, is blowing intermittently. This continental air drastically reduces the humidity. During the other months it is generally raining. During the rainy season, the amount of radiation received at the ground is considerably reduced because it is intercepted by clouds. It is wrong, therefore, to consider that in humid tropical regions radiation and rain are not limiting factors. Extensive work has been done concerning water and energy exchanges of forests in temperate regions. Fewer workers have investigated this subject in tropical rain forest. Some attempts have, nevertheless, been made (e.g. Allen et al., 1972; Lemon et al., 1970; Huttel, 1975). It is very difficult to measure the energy exchanges of a tropical rain forest because of the great heterogeneity in species and tree sizes. Furthermore, leaf fall and the growth of young leaves do not occur in the same period for all species. Some trees show some periodicity, and they are leafless for 3 to 5 weeks, whereas with other trees, the leaves are renewed continuously.

The purpose of this study is to provide tropical countries with data that can be used for their development. Water balance studies must lead to a general overview of the water conditions in an area and of the suitability of the region for the cultivation of a particular crop. It is well known that forests, by virtue of the large area they cover can affect the climate, especially air temperature and the amount of water vapour and carbon dioxide in the atmosphere. In tropical regions, the equilibrium of the tropical rain forest ecosystem is endangered by the reduction of its area induced by the necessity to feed the rapidly growing population and to produce raw material. The substitution of this humid tropical rain forest by agricultural crops may introduce some modifications into the atmosphere-canopy exchanges and alter the atmospheric characteristics. Generally, single species of trees such as Hevea, Oil Palm, Terminalia or Okoume are used for afforestation.

Our attention will be focused on the analysis of the energy balance of a Hevea forest stand located near Abidjan (Ivory Coast). The study of the energy flux through the biological system should give some knowledge of the microclimate and perhaps indicate how the plant community may affect the climatic conditions. The Hevea forest plantation has been selected for two reasons (1) homogeneity and (2) annual leaf renewal. The physiological system of the Hevea causes the foliage to grow older at the same rate, and the canopy can be considered as acting as a single leaf, which is easier to study. Our first results concern the importance of the radiational energy available to the canopy and its partition in different processes. The energy balance-Bowen ratio method was used to determine forest heat, water vapour and carbon dioxide exchanges.

METHODS

Basic Considerations

The fundamental concept which governs ecology is energy exchanges; in our case it concerns particularly heat transport. The energy absorbed Rn by the rubber forest stand is partitioned by different processes in the boundary layer. Assuming horizontal homogeneity, the energy budget of the forest can be written as:

$$Rn = H + \lambda E + G + \mu F_c + J_{(H+W)}, \quad (1)$$

where λ is latent heat of vaporization of water ($J\ kg^{-1}$); μ is the specific energy equivalent of CO_2 fixation ($J\ kg^{-1}$). The forest-atmosphere interactions can be analyzed through the energy budget. Some of these terms act as sources (heat, water vapour) and some as sinks (momentum, CO_2).

Various methods have been reported in the literature concerning measurements of the exchange of heat energy (e.g. Thom et al., 1975; Stewart and Thom, 1973; Perrier, 1975; Itier, 1980; Thom, 1979; Spittlehouse and Black, 1980; Jarvis et al., 1976 and Ripley and Saugier, 1973). The Energy Budget-Bowen ratio technique was used to partition the available energy between λE and H. The equations governing latent and sensible heat exchange above the canopy are:

$$\lambda E = -\frac{\rho c_p}{\gamma} \cdot K_W \, (de/dz) \quad \text{and} \quad (2)$$

$$H = -\rho c_p \, K_H \, (dT/dz), \quad (3)$$

where de is the water vapour pressure difference between levels z_1 and z_2, dT is the air temperature difference between z_1 and z_2 and dz is the distance between z_1 and z_2. Assuming that the transfer coefficients for sensible heat and water vapour are equal ($K_H \equiv K_W$), the Bowen ratio can be written as:

$$\beta = \frac{H}{\lambda E} = \gamma \frac{dT}{dz} . \quad (4)$$

In the same way, if the equation of CO_2 exchange above the canopy is:

$$\mu F_c = \mu\omega\rho \, K_c (dC/dz), \quad (5)$$

another ratio can be defined as the ratio of photochemical energy flux density to latent heat flux density (Allen et al., 1974)

$$\alpha = \frac{\mu F_c}{\lambda E} = \frac{K_c \mu\omega\rho \, (dC/dz)}{-K_W \frac{\rho c_p}{\gamma} (de/dz)} \quad (6)$$

where dC is the carbon dioxide concentration difference between levels z_1 and z_2 and ω the ratio of densities of CO_2 and dry air. Since CO_2 uptake and transpiration process are occurring in the opposite way α will be positive. Assuming $K_C = K_W$

$$\alpha = - \frac{\mu\omega\gamma}{c_p} \cdot \frac{dC}{de} . \quad (7)$$

Latent and sensible heat flows and the photosynthetic flux density are calculated from:

$$\lambda E = \frac{Rn - G}{(1 + \beta + \alpha)} , \quad (8)$$

$$H = \frac{\beta (Rn - G)}{(1 + \beta + \alpha)} \text{ and} \quad (9)$$

$$\mu F_c = \frac{\alpha (Rn - G)}{(1 + \beta + \alpha)} . \quad (10)$$

The Bowen ratio approach also assumes that there is neither horizontal heat or water vapour advection beneath the top measurement height, nor net vertical mass flow of air transporting heat and vapour to or from the canopy.

The resistance to sensible heat exchange in the interface "canopy-air" is an aerodynamic resistance (r_{as}), whereas the latent heat resistance is conceived as the sum of an aerodynamic resistance (r_{aw}) and a surface resistance (r_c) such that:

$$r_{as} = - \rho c_p \, (dT/H) \text{ and} \quad (11)$$

$$r_{aw} + r_c = - \frac{\rho c_p}{\gamma} \cdot \frac{de}{\lambda E} . \quad (12)$$

If similarity between the transfer coefficients for sensible heat and water vapour is assumed, then the boundary layer resistances of the canopy to mass transfer are equal ($r_{aw} = r_{as} = r_a$). A simple micrometeorological model describing the water vapour exchange between the plant canopy and its environment has been given by Penman (1956) and completed by Monteith (1965). The general expression of the model shows that the energy budget (Equation 1) and the aerodynamic equations (11, 12) for evaporation can be combined to give an expression for evapotranspiration rates of vegetative surfaces using measured climatic parameters:

$$\lambda E = \left(\frac{\Delta}{\Delta + \gamma}\right) (Rn - G) + \left(\frac{\gamma}{\gamma + \Delta}\right) \left(\frac{(e_{s(z)} - e_{(z)})/r_a}{1 + (r_c/r_a)}\right) . \quad (13)$$

Site and Instrumentation

Site. Two main seasons exist in Western Africa, a wet and a dry which roughly correspond to the periods of influence of each of the two air masses separated by the Intertropical Convergence Zone

ITCZ and their associated winds. The wet season is associated with moisture laden southwesterly winds and the dry season with dry, more dusty northeasterlies. The duration of each season depends upon the prevalence of these air masses.

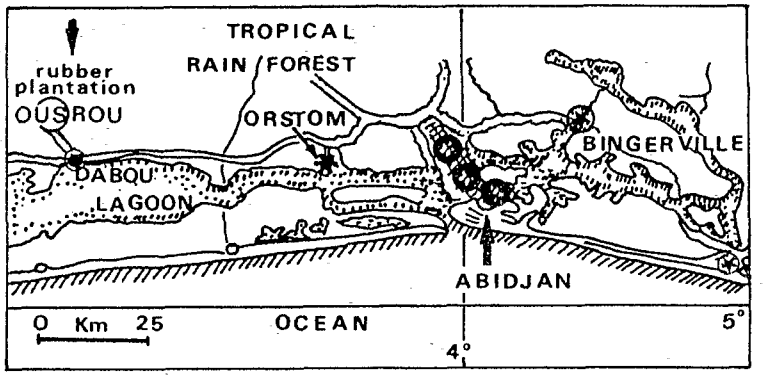

Figure 1. Location of the Hevea brasiliensis plantation (near Ousrou)

The rubber forest or the Hevea brasiliensis plantation is located at Ousrou, 57 km west of Abidjan (Figure 1). The climatic of the region is under the influence of the position of the ITCZ which determines four weather periods with their corresponding characteristics: two rainy seasons, May to July and October to November alternating with two dry seasons. Occasionally, in December and/or January, the ITCZ moves south resulting in hot dry continental air from the north (Harmattan) blowing over the tropical rain forest (Figure 2). Savanna fires driven by these winds enhance the CO_2 concentration in this air mass (Monteny et al., 1983). During the dry season when the trade winds are weak, the land and sea breeze circulation resulting from land-ocean temperature differences is well developed. This introduces some modifications in the energy exchange processes, as we shall see later.

The rubber forest represents a very large area, between 12 and 14,000 ha on almost horizontal land with an elevation variance of less than 20 m. Our experimental station (Figure 3) is located in a homogeneous plot of 25 ha with 19 year old rubber trees, 23.5 m high, inside an extended plantation with a density of 380 trees/ha. The average biomass of the upper part of the forest stand is 159 metric tons of dry matter/ha. The rubber trees are deciduous with defoliation occurring generally in February and

refoliation completed in March. The leaf area index varies from one year to the other, but the average is 4.3 ± 0.5. The vertical leaf distribution is between 12 m and the top of the trees with the highest density above 18 m.

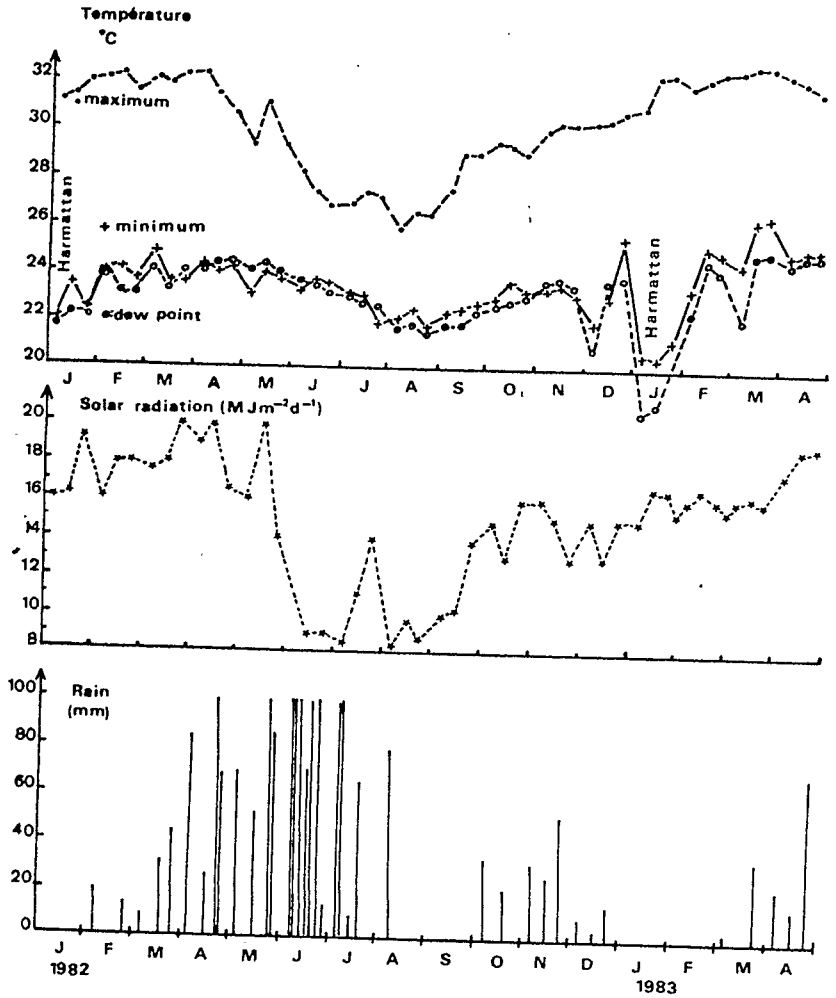

Figure 2. Evolution of the climatic conditions at Ousrou during the experiment.

A 22 m high open frame tower equipped at its top with a platform of 2 m^2 was erected in this plot. From this, an 11 m high mast was mounted on which the sensors are fixed (Figure 3).

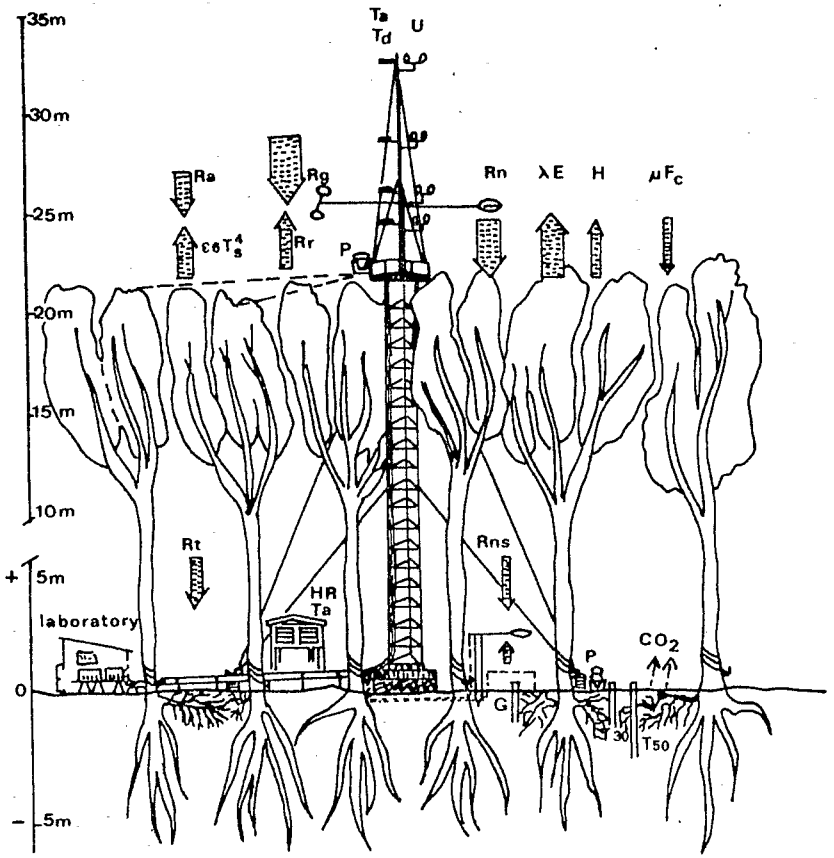

Figure 3. Experimental station in a hevea forest (Ousrou)

Rg : global radiation
Rr : reflected radiation
Ra : atmospheric radiation
$\varepsilon\sigma T_s^4$: soil and canopy radiation
Rn : net radiation
Rt : transmitted radiation
P : rain gauge
T : temperature sensors
U : wind speed sensors

E : evapotranspiration rate
λ : latent heat of vaporization
H : sensible heat (air)
G : sensible heat (soil)
μF_c : flux of CO_2 in air
$T_{30}T_{50}$ soil temperature
Ta : air temperature } on the floor
HR : air humidity }
Rns : net radiation at the ground

The height of 33 m is necessary to record the relatively small gradients of temperature, dew point, CO_2 concentration and windspeed (Monteny et al., 1981b). Instrument heights for the 1982, 1983 measurements are summarized in Table 1. CO_2 flux from the soil was measured by the method used by Perrier et al. (1977).

Table 1. Disposition of the sensors on the mast, 1982 - 1983.

	Height (m)			
Sensors	25.1	28.0	30.0	33.0
Pyranometer		X		
Net Pyrradiometer		X		
Anemometer	X	X	X	X
Thermocouple	X	X	X	X
Water vapour		X		X
Carbon dioxide		X		X

Instrumentation. Incident and reflected solar radiation were measured with Kipp phyranometers fixed on a boom extending 3 m to the south, 4 m above the canopy. A Schenck net pyrradiometer was mounted on the same boom. Air temperature was measured by thermocouples (copper-constantan) placed at different levels above the canopy and compared with a 0° ice-liquid water reference temperature. A direct dT measurement, although more appropriate, has shown that a loss of accuracy occurs due to interference effects originating from surrounding equipment and from the signal leads. Another point is that only positive signal of the D.C. output can be integrated whereas temperature inversions may take place. The data were registered on a series of Time Electronics voltage integrators powered by a 12 V D.C. battery. Integrator sensitivity was 30 counts s^{-1} (1/30 mV s or 1/10 mV s) with a zero stability less than 1 $\mu V°C^{-1}$. All the integrators were calibrated in the field to remove the effects of the variability of the calibration constant between the laboratory and outside conditions, particularly with respect to temperature and air humidity. Based on the recommendation of Mc Neil and Shuttleworth (1975) two pumps (vibrator swinging magnet type) drew the air from different levels above the canopy for the water vapour and carbon dioxide measurements. The draft lines (teflon tubing) are of equal length. Water vapour concentration was determined by a single dew point hygrometer. Carbon dioxide

concentration was measured with an ADC infrared gas analyser (IRGA) of the type design by Saugier and Ripley (1974). Because of the importance of the water vapour content in the air, it was first dried by condensation in a cold bath then brought up at 35°C. The two air streams were flowing into two cells of the IRGA which provided the differential CO_2 measurements. No correction has to be applied to recover the original CO_2 density of the air. Webb et al. (1980) gave clear indication that the measured CO_2 density difference is equivalent to the difference of CO_2 mixing ratio relative to the dry air component and leads to the true CO_2 flux. Another ADC IRGA registered the absolute CO_2 concentration evolution at the highest level (33 m). The wind speed was recorded by Casella anemometers which were calibrated by comparison with a reference anemometer. Every 15 min., the registered data from the different sensors stored in a data acquisition system were printed. The different energy fluxes were calculated with an HP 41 CV as the work proceeded. They represented the mean value of a 15 min. integrated time.

Error analysis. The importance of the errors in estimating the fluxes are due to errors on measurements of the constituent input parameters. The relative errors are determined by using the maximum expected measurement error for each parameter. An accuracy of 6% was assumed for measurements of net radiation and of 20% for soil heat flux. The thermocouple integrator assembly suggested that maximum differential temperature errors should be 0.1°C. The water vapour pressure determined by the dew point hygrometer had a maximum error of 0.2 mb at 30°C. The error of CO_2 gradient was assumed to be 0.5 ppm with our differential CO_2 measurement method. The relative errors are calculated by differentiating Equations 8, 9 and 10. The errors in λE ($\sigma\lambda E$), H (σH) and μF_c ($\sigma\mu F_c$) are estimated from:

$$\frac{\sigma\lambda E}{\lambda E} = \frac{\sigma Rn + \sigma G}{|Rn + G|} + \frac{|\beta|\left(\frac{2\sigma T}{|dT|} + \frac{2\sigma e}{|de|}\right) + |\alpha|\left(\frac{2\sigma C}{|dC|} + \frac{2\sigma e}{|de|}\right)}{1 + |\beta| + |\alpha|} \quad (14)$$

$$\frac{\sigma H}{H} = |\beta|\left(\frac{2\sigma T}{|dT|} + \frac{2\sigma e}{|de|}\right) + \frac{\sigma\lambda E}{\lambda E} \quad (15)$$

$$\frac{\sigma\mu F_c}{\mu F_c} = |\alpha|\left(\frac{2\sigma C}{|dC|} + \frac{2\sigma e}{|de|}\right) + \frac{\sigma\lambda E}{\lambda E} \quad (16)$$

Results are presented in Table 2. Values of Rn, dT and de were established for times of maximum and minimum λE. The relative error on each flux depends on the sign and value of β and α. Small errors in de and dC introduce large errors in λE and μFc. This occurs generally in early morning, late afternoon and when

solar energy is occluded by clouds. But when Rn is low, λE and μF_c rates are so small as to be of little interest. This is no longer the case with old tree foliage in a very high air water vapour content (December 28, 1982). Large errors are then introduced in the estimation of λE and μF_c because of the weakness in the water vapour pressure gradient inducing a large value of β. For β between 0 and 0.6, the maximum relative errors for λE and μF_c are under 20%.

Table 2. Analysis of the energy balance-Bowen ratio method for three days. Data are of measurements made at the time of maximum and minimum λE.

Dates	Hours	Rn+G	β	α	λE	$\frac{\sigma\lambda E}{\lambda E}$	H	$\frac{\sigma H}{H}$	μF_c	$\frac{\sigma\mu F_c}{\mu F_c}$
04.19	13.00	610	.18	-.035	520	0.11	94	0.16	-18.2	0.12
1982	16.00	146	.76	-.067	85	0.30	64	0.68	- 5.8	0.33
12.28	13.00	389	.35	-.063	167	1.27	225	3.89	-10.5	1.39
1982	16.00	165	.61	-.027	63	1.25	101	4.23	- 1.7	1.30
01.07	13.00	431	.09	-.021	397	0.10	34	0.13	- 8.4	0.10
1983	16.00	139	.08	-.016	128	0.11	10	0.16	- 2.0	0.11

RESULTS AND DISCUSSION

Radiation Budget

The net radiation flux density (Rn), an important climatic characteristic, represents the amount of energy available to canopy processes such as transpiration and photosynthesis. Figure 4 shows the diurnal course of the incident solar radiation (Rg) the net radiation above the canopy (Rn) and near the ground (Rns) and the albedo for the short wave radiation (Rr/Rg). The fluctuations in solar radiation are a result of the advective clouds formed in this coastal region.

The following relations were obtained between net radiation and incident solar radiation where Rn and Rg are expressed in $W\ m^{-2}$:

Humid atmosphere (water vapour pressure: 28 to 32 mb);
young leaf canopy $Rn = 0.72Rg - 4.0$ $n = 282$ $r^2 = 0.98$
old leaf canopy $Rn = 0.70Rg - 0.8$ $n = 154$ $r^2 = 0.96$
without foliage $Rn = 0.62Rg + 4.0$ $n = 125$ $r^2 = 0.98$
Dry atmosphere (water vapour pressure: 8 to 10 mb);
old leaf canopy $Rn = 0.78Rg - 50.0$ $n = 113$ $r^2 = 0.96$.

The slope of the relationships between the incident solar radiation and the net radiation is quite constant. The only

marked difference which significantly changes the slope of the relation is the period when the trees are leafless and during the Harmattan, when dry air blows over the region. The reflection coefficient (Rr/Rg = albedo) does not change markedly with solar elevation. At low solar elevation, a large proportion of the incident solar radiation is trapped by multiple scatterings caused by the roughness of the canopy surface while at high solar elevation, the incident solar radiation penetrates deeper and more arrives below the canopy (Figure 4). Our mean daily albedo coefficient varies from 0.13 to 0.16. The different absorption and reflection of photosynthetically active radiation and near infrared radiation (Matt et al., 1978) also may affect the albedo values with time of year. Due to the importance of the water vapour concentration in the atmosphere, the long wave radiation budget has little influence on the net radiation flux. This is not the case when dry continental air is blowing over the coastal region as can be seen from equations above.

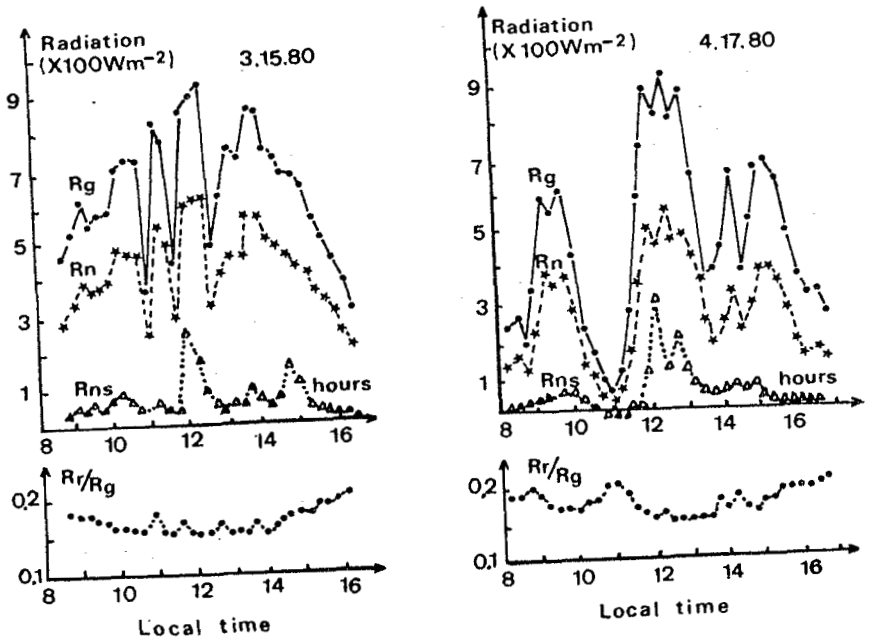

Figure 4. Evolution of the incident solar radiation (Rg) of the net radiation above the Hevea canopy (Rn) and on the floor (Rns) and the albedo (Rr/Rg) at the beginning of forest refoliation and one month later.

Diurnal Energy Balance

Evapotranspiration rates. Equation 1 has a term $J_{(H+W)}$ which represents the physical heat storage per unit horizontal area (for a unit volume of the forest). Barbier (1983) calculated $J_{(H+W)}$ for different hours of a day and found it to be relatively small: 10 to 25 W m^{-2} representing 3 to 7% of the net radiation. He noted that the heat storage fluctuation was highest a few minutes after the net radiation input had changed, but only for the upper part of the forest system. It is only with sunrise and sunset that the heat storage was very high on an hourly basis. In our case, the heat storage was considered to be relatively small between 0900 and 1600 hours and has, therefore, been neglected. The results of the energy balance of a soil-forest-atmosphere system in a tropical humid region are illustrated in Figures 5 and 6. A comparison between two days is given in Figure 5. The first day is April 9, 1982 with no evident restriction on water availability in the soil. The latent heat flux (λE) during the afternoon was proportional to the net radiation Rn, representing 80% of it. During the morning hours, our measurements of the vertical water vapour pressure gradients showed an inversion which gave a negative value to β. Actually, this was due to the importance of night radiation cooling which produced cloud fog above the forest vegetation (10 to 30 m above the surface) and water condensation on the forest foliage. The importance of dew in humid tropical forest is well known. In the early morning hours, fog lifted and the water vapour pressure was higher than closer to the foliage surface where water vapour had condensed. This gave the impression that water vapour was advected to our system, giving positive values of λE.

The second day, April 1, 1983, had a soil water potential at -0.31 MPa in the first 1.20 m of soil after an exceptionally severe dry season (Figure 2). The latent heat flux increased during the morning and by the afternoon represented 50 to 60% of the net radiation. This was due to the restricted water availability in the soil and also to the desication of a great number of non-woody root hairs of the surface root system. Note that during this period solar radiation was variable due to the advective clouds. This frequent fluctuation of energy induced a wide variation in the canopy temperature.

Figure 6 represents the heat flux evolution of the rubber forest stand for two different climatic conditions, but nearly at the same soil water availability.

The first condition is represented by December 28, 1982. Our forest stand was under the sea breeze circulation, especially in the morning when land and sea breeze mix. The cooler and more humid sea breeze (water vapour pressure: 28 to 34 mb), advected across the coast and vegetation under the warmer land air. The water vapour pressure deficit between foliage and air mass was only 3 to 7 mb. The advancing sea breeze front produced uplift in

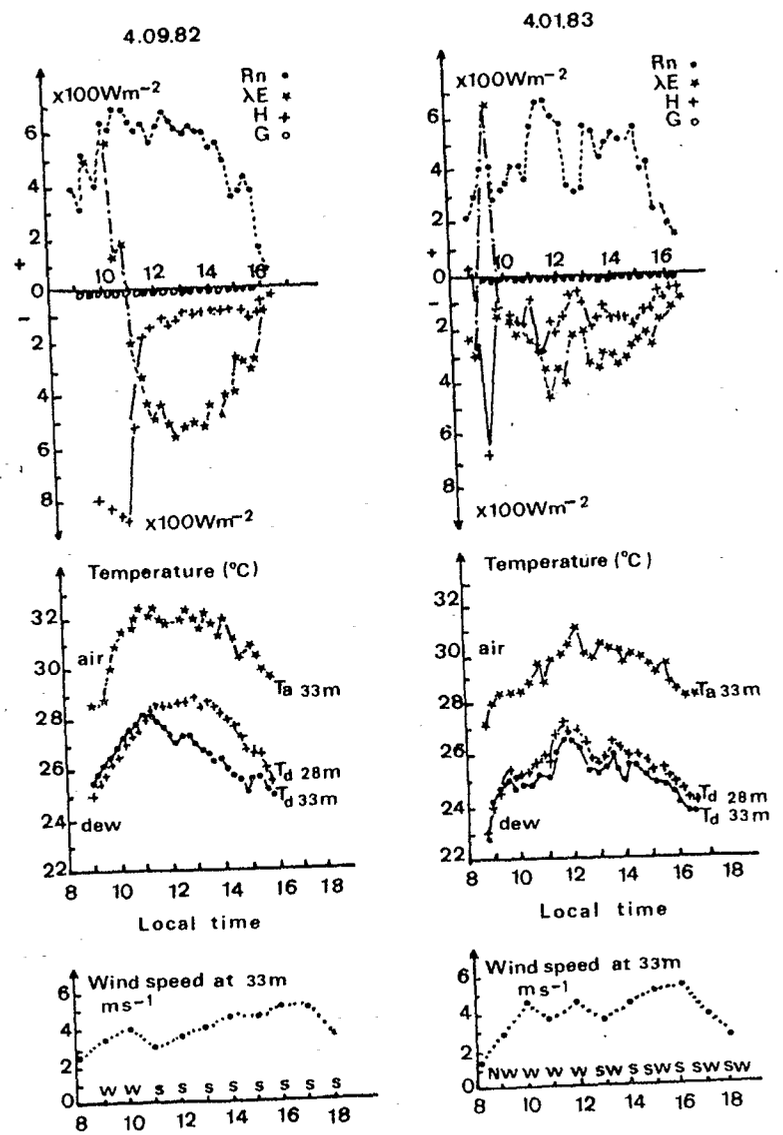

Figure 5. Diurnal variation of the instant fluxes of net radiation (Rn), sensible (H) and latent (λE) atmospheric heat, soil heat (G), air (Ta) and dew (Td) temperature and wind speed above the Hevea forest during two different days.

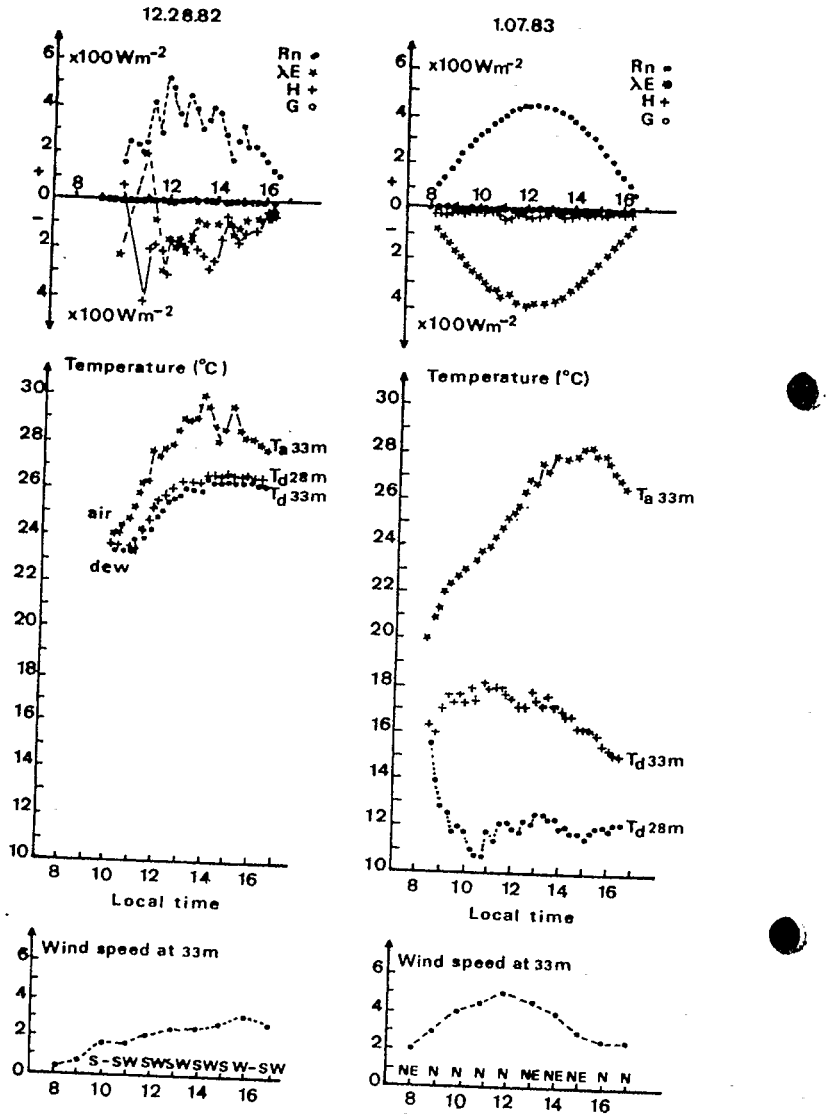

Figure 6. Diurnal variation of the instant fluxes of net radiation (Rn), sensible (H) and latent (λE) atmospheric heat, soil heat (G), air (Ta) and dew (Td) temperature and wind speed above the Hevea forest during two different days.

what was already an unstable air mass over the land. The latent heat flux was only 45 to 55% of the net radiation compared to the 80% measured in April 1982, just after the trees refoliation. It seemed that, in the same climatic conditions, the stomatal activities were reduced due to physiological factors induced by the age of the leaves. The measurements of the trunk girth showed a very weak retraction at the same time. Thus, the stable marine air was warmed over the forest stand producing a more unsteady boundary layer. The breeze front was commonly associated with the development of sea breeze cumulus clouds which reduced the net radiation as observed at 10 to 15 hours.

During the day of January 7, 1983, the rubber forest stand was under the influence of continental air (Harmattan) which is very dry (water vapour pressure: 8 to 13 mb). The partition of the heat fluxes was very different than before, although water availability in the soil was lower than in December 1982 (soil water potential -0.08 MPa). Latent heat flux represented ≈ 90% of the net radiation input. Under these conditions, not only was radiative energy the driving power of the exchanges, but also, the water vapour deficit (vpd) between the tree foliage and the air. Under these extremely dry air conditions, when the first 1.20 m in the soil were drying up (soil water potential -0.11 MPa) it appeared that absorption by the tap roots occurred 2.0 to 3.5 m deep and that the water stored in trunks and branches was involved in the transpiration process causing the trunk girth to retract more than normal. The suction force in the roots was increased by the intensity of the surface to air water vapour concentration gradient. This showed that the forest stands were acting as a very good buffer on the air properties (temperature and humidity).

The evaporation rates of forest stands are quite different than those of a short annual vegetation which, in the same conditions, will be dry (Monteny et al., 1981a). This means that if forest is substituted by another canopy which doesn't function in the same manner, the energy exchanges are different and can therefore modify some climatic characteristics. For the same solar energy input, if less water vapour is injected in the atmosphere by evapotranspiration, more sensible heat will be registered which influences ~~are~~ air temperature.

In order to estimate forest evapotranspiration from some practical measurements such as net radiation, we present the relation obtained between net radiation and the measured latent heat flux for different soil and climatic conditions (Figure 7). For all days under the influence of the oceanic air, with a water vapour pressure deficit of 3 to 12 mb:

a) the latent heat flux of trees with young leaves and high soil water availability has the following equation;
$\lambda E = 0.82 Rn - 21$ (W m^{-2}) $r^2 = 0.90$;

b) if the availability of soil water is restricted, the water consumption by the forest stand is reduced and the equation becomes;
$\lambda E = 0.70Rn - 4$ $(W\ m^{-2})$ $r^2 = 0.71$; and

c) for trees with older foliage (10 to 11 months) and no soil water restriction, the relation is
$\lambda E = 0.48Rn - 22$ $(W\ m^{-2})$ $r^2 = 0.69$.

These results show that the evapotranspiration rates are progressively reduced by the activity of the stomata. As a matter of fact the stomatal apertures of young leaves are much better regulated as a function of the soil water availability and the incoming radiation than in older leaves. In other words, the stomatal behaviour for the same pedoclimatic conditions changes with their physiological age.

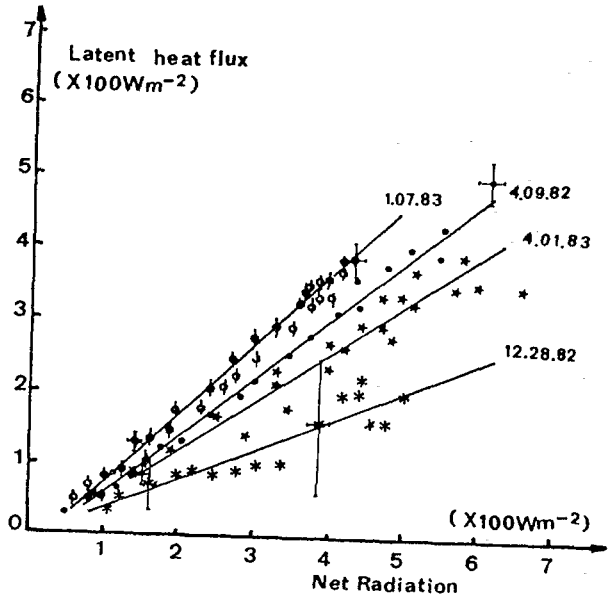

Figure 7. Relationship between latent heat flux and net radiation input for different ageing periods of the Hevea foliage (instant values from 9 to 17 hour).

For days under the influence of continental air, the latent heat flux rises considerably in spite of the old leaves as a consequence of the increase of the air water vapour pressure deficit:

$\lambda E = 0.95Rn - 52$ $(W\ m^{-2})$ $r^2 = 0.79$.

The regression curves for λE vs Rn would probably have less "noise" if longer time periods were taken instead of 15 min. samples. In fact, on partly cloudy days the net radiometer responds locally to the conditions while the latent heat flux is an average value generated over a larger forest surface that is swept past the tower.

To have a better idea of this interaction of climatic and soil conditions upon the water vapour exchanges, the calculated canopy surface resistance from Equations 11 and 12 is represented in Figure 8. The evolution during the day of the canopy resistance r_c begins generally with low values due to the presence of dew on the foliage. After dew has evaporated the actual value of r_c represents the equilibrium situation depending on the soil water availability and on the importance of the air water vapour deficit. It is only during the afternoon hours, with the decrease of solar energy that the forest surface canopy resistance increases.

Canopy resistance varies from 30 to 100 s m^{-1} with vpd between 5 and 12 mb, which is generally the case for oceanic air. With these conditions, leaf age and increasing soil water depletion influence the surface resistance since it is largely of physiological origin. With continental air above the forest stand (vpd > 15 mb), the forest surface resistance varies between 400 and 1200 s m^{-1} (January 7, 1982) and in addition, when soil water content decreases (-0.1 to -0.23 MPa) (January 26, 1982) the surface resistance increases and ranges from 800 to 1800 s m^{-1}. These relationships might be considered as characteristic of a particular combination of tree species soil and climatic conditions and may be used in a model (e.g., Halldin et al., 1979; Perrier et al., 1980).

Modeling Hevea forest evapotranspiration. To evaluate the Hevea forest evapotranspiration, ETM, it is necessary, for practical use, to have a limited amount of basic information (climate and plant responses).

The equilibrium evapotranspiration rate ET_o may be expressed as the first term of Equation 13.

$$ET_o = \left(\frac{\Delta}{\Delta + \gamma}\right)\left(\frac{Rn - G}{\lambda}\right) \quad (mm\ d^{-1}) \qquad (17)$$

The introduction of a crop coefficient, C, will allow the estimation of the maximum water consumption, ETM, of the Hevea forest. This coefficient characterizes the importance of the stomatal regulation (Perrier et al., 1980) to soil or to meteorological factors. Its value is experimentally determined. Priestley and Taylor (1972) found that C had a value near 1.26 for a number of cases. Lhomme and Monteny (1982) obtained C = 1 for the south part of Ivory Coast conditions and for short crop

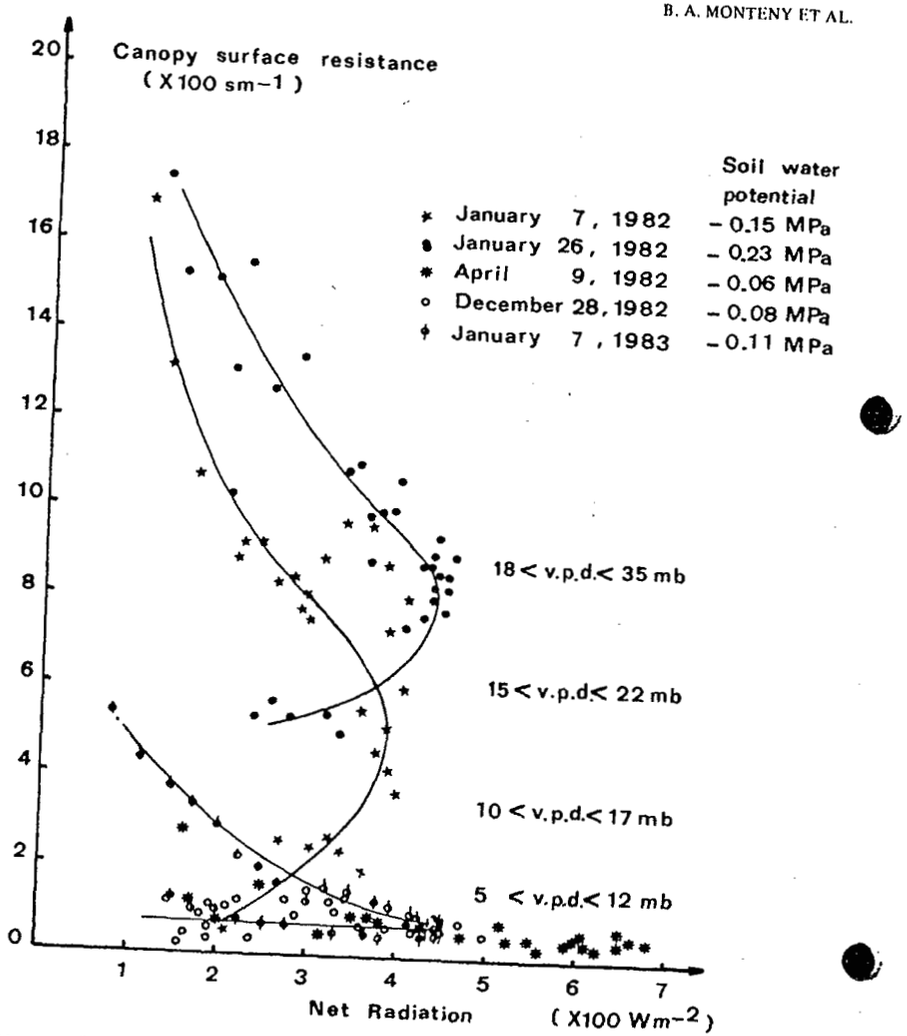

Figure 8. Relationship between net radiation input and the canopy surface resistance for different climatic and soil conditions (vpd = water vapour deficit of air).

canopies with enough soil water. Maximum water consumption is restricted only by the net radiation input. McNaughton and Black (1973) found C equal to 1.05 for a Douglas fir forest. Equation

17 does not take into account parameters such as soil temperature or foliage age with interfere with the stomatal regulation.

In the case of a Hevea forest located in the humid trophical regions of West Africa, the following values are proposed for C (Table 3) to estimate the water consumption during the period of foliage activity. Thus, using these values in Equation 17, without any restriction of soil water, the total amount of water consumption for the Hevea forest in our climatic conditions varies from 920 to 990 mm y^{-1}. The more important factors which act on the geographical repartition of Hevea plantations are rain distribution, as can be seen in Figure 2, and water storage capacity of the soil.

Photosynthesis. In the case of the CO_2 assimilation rate of a rubber forest stand, the canopy layer is a layer possessing an upper and lower boundary. The trunk zone is devoid of foliage. Thus, the canopy layer is a sink region which is supplied by carbon dioxide from the soil and from the atmosphere. Carbon dioxide fluxes from the soil are a function of microorganism activities and of the humidity and temperature in the top 20 cm of the soil. The flux of CO_2 from the soil varies between 0.6 and 1.2 10^{-7} kg $CO_2 m^{-2} s^{-1}$ but no significant variation has been measured during the day. The accuracy of the measurements is 18%. Figure 9 illustrates the fraction of energy used by the canopy photosynthesis in relation to the net radiation. When the canopy foliage is young and well watered, the carbon dioxide assimilation rate is very high compared to the same foliage 10 months older. The reduction of the foliage photosynthesis is 35 to 45% for the same energy input (Rn) with an energy efficiency representing 4 and 2.5% respectively. In addition to the decrease of canopy assimilation rate due to the foliage age, a higher reduction is noted when soil water availability is low. The rate between canopy photosynthesis and energy input is then no longer constant and is depressed by the soil water shortage. The decreasing phase, when water deficit closes the stomata, does not coincide with the increasing phase of the morning hours; the more drastic the water deficit in the soil, the more it lowers the assimilation efficiency. When the water vapour pressure deficit of the air increases (Harmattan) both latent heat flux and photosynthetic flux increase (January 7, 1983).

The results used to draw these relationships are from afternoon hours. In fact, the characteristics of the atmosphere above the forest are conditioned by the night CO_2 exchange coming from the soil and the vegetation respiration. This is why the general diurnal trends in the carbon dioxide content of the air show a marked amplitude of the night time increase associated with low wind. This amplitude of the diurnal trends, with a maximum at night and minimum usually during the afternoon, is associated not only with the photosynthetic absorption of CO_2 but, also, with the

Table 3. Values of the plant coefficient C.

Air origin	Foliage	Soil water[a]	Values of C	Month
Oceanic	Young	120-200 mm	0.85<C<1.00	March-April
Oceanic	Young	>200 mm	0.95<C<1.10	April-August
Oceanic	Young	120-200 mm	0.75<C<0.90	Sept.-October
Oceanic	Old	>200 mm	0.50<C<0.80	Nov.-December
Continental	Old	120-200 mm	1.00<C<1.25	Dec.-January
Oceanic	Old	60-120 mm	0.40<C<0.60	January

a. fraction of extractable water in the root zone.

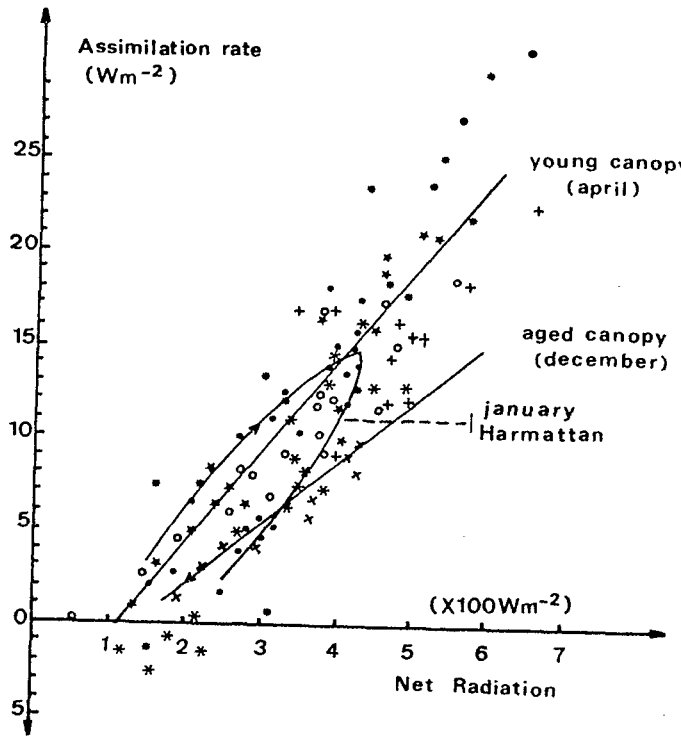

Figure 9. Relationship between instant net radiation and the CO_2 assimilation rate by the Hevea foliage for different conditions.

change of air trajectory in the surface boundary layer in relation to land and sea breezes (Monteny et al., 1983).

CONCLUSION

The study has shown that during the whole vegetative growing period of a rubber stand, the radiation budget is nearly constant. This is very similar to what is observed in tropical rain forests. The radiation budget is disturbed only during 1 to 2 months when the rubber forests are leafless and the solar energy penetrates more deeply into the stand down to the soil.

The energy budget, which is actually divided into latent heat and sensible heat, depends more upon the soil water availability and the leaf age than upon the air water vapour pressure deficit which acts only when continental air is blowing (2 to 3 weeks per year in December-January). Thus it cannot be considered as an important environmental factor for tropical rain forest most of time under dominant oceanic trade winds. The diffusion gradient from the inside to the outside of the leaf is small. To estimate the daily water consumption of the Hevea forest we suggest the use of the radiative expression of the Penman equation modulated with a crop coefficient which takes account of the plant factors induced by the soil and climatic conditions. The rubber plantation with young leaves releases an important amount of water vapour in the atmosphere representing 3 to 5 mm a day with a good supply of soil water and 1 to 3 mm a day when soil water availability is low and the foliage is older. Short vegetation, generally annual plants, grow only 6 to 8 months a year, leaving the soil uncovered for 4 to 6 months. This introduces great modification into the energy exchanges, more heat is released into the atmosphere and the air temperature rises.

The photosynthesis of this forest is very difficult to measure accurately because, in our climatic conditions, the carbon exchanges are under the influence of the wind origin. However, the assimilation rate of the Hevea stand is very high 20 W m^{-2} ($1.8\ 10^{-6}$ kg CO_2 m^{-2} s^{-1}) when the leaves are young and well supplied with water. It seems that there is a gradual reduction of photosynthesis as the leaves grow older. Large scale vegetation such as tropical rain forest and other tropical tree plantations of rubber, oil palm, cocoa and coffee not only maintain the original equilibrium of the oceanic atmosphere, but inject a great quantity of water into it. This water once condensed into clouds goes on to give rainfall in the savanna regions downwind.

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REFERENCES

Allen, L.H. Jr., E. Lemon, and L. Müller: 1972. Environment of a Costa Rican forest. Ecology 53:102-111.

Allen, L. M., R.J. Hanks, J.K. Aase, and H.R. Gardner: 1974. Carbon dioxide uptake by wide-row grain sorghum computed by the profile Bowen ratio. Agron. J. 66:35-41.

Barbier, J.M.: 1983. Bilan d'énergie et évapotranspiration d'un couvert d'Hevea brasiliensis en Côte d'Ivoire. Thèse Université de Paris Sud. 172 pp.

Halldin, S., H. Grip, and K. Perttu: 1979. Model for energy exchange of a pine forest canopy. pp. 59-75 in Comparison of forest water and energy exchange models, Vol. 9, Forest Ecology, ed. by S. Halldin.

Huttel, C.: 1975. Recherches sur l'écosystème de la forêt subéquatoriable de basse Côte d'Ivoire. Estimation du bilan hydrique. La Terre et la Vie 29:192-202.

Itier, B.: 1980. Une méthode simplifiée pour la mesure du flux de chaleur sensible. J. Rech. Atmos. 14:17-34.

Jarvis, P.G., G.B. James, and J.J. Landsberg: 1976. Coniferous forest. pp. 171-240 in Vegetation and the Atmosphere, Vol. 2. ed. by J.L. Monteith. Academic Press, New York.

Lemon, E., L.H. Jr. Allen, and L. Müller: 1970. Carbon dioxide exchange of a tropical rain forest. Bio-Science 20:1054-1059.

Lhomme, J.P., and B.A. Monteny: 1982. Présentation d'une formule d'estimation de l'évaporation potentielle conforme aux nouvelles recommandations internationales. Arch. Met. Geoph. Biokl. (B) 30:253-260.

Matt, D.R., R.T. McMillen, and B.A. Hutchison: 1978. Spectral radiation balances above an oak-hickory stand during the spring leafing season. pp. 217-219 in Symposium on forest meteorology. WMO no. 527.

McNaughton, K.G., and T.A. Black: 1973. A study of evapotranspiration from a Douglas-fir forest using the energy balance approach. Wat. Resources Res. 9:1579-1590.

McNeil, D.D. and Shuttleworth, W.J.: 1975. Comparative measurements of the energy fluxes over a pine forest. Boundary-Layer Meteorology 9:297-313.

Monteith, J.L.: 1965. Evaporation and environment. Symp. Soc. Exp. Biol. 19:205-234.

Monteny, B.A., J. Humbert, J.P. Lhomme, and J.M. Kalms: 1981a. Le rayonnement net et l'estimation de l'évapotranspiration en Côte d'Ivoire. Agric. Meteor. 23:45-59.

Monteny, B.A., J.M. Barbier, J.P. Lhomme: 1981b. Exchanges radiatifs et bilan d'énergie d'un couvert d'Hevea. Rapport ORSTOM pp. 28.

Monteny, B.A., J.M. Barbier, and C. Omont: 1983. Mesure des flux de CO_2 au niveau d'un couvert d'Hevea brasiliensis. 31 pp. Colloque Ministère Recherche et Industrie Piren/Cnrs. Meudon.

Penman, H.L.: 1956. Evaporation: an introductory survey. Neth. J. Agric. Sci. 4:9-29.

Perrier, A.: 1975a. Etude physique de l'évapotranspiration dans les conditions naturelles. II Expression et paramèters donnant l'évapotranspiration réelle d'une surface. Ann. Agron. 26: 105-123.

Perrier, A.: 1975b. Etude physique de l'évapotranspiration. III Evapotranspiration réelle et potentielle des couverts végétaux. Ann. Agron. 26:229-243.

Perrier, A., B. Itier, and B. Jaussely: 1977. Etude de la photo-synthèse en plein champs. pp. 113-136 in Les processus de la production végétale primarie, ed. by A. Moyse. Gauthier-Villars, Paris.

Perrier, A., N. Katerji, G. Gosse, and B. Itier: 1980. Etude de l'évapotranspiration réelle d'une culture de blé. Agric. Météor. 21:295-311.

Priestley, C.H., and R.J. Taylor: 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Weather Rec. 100:81-92.

Ripley, E.A., and B. Saugier: 1973. Micrometeorology. VI Fluxes of radiation, matter and energy. Technical Report no. 25, Matador Project, University of Saskatchewan.

Saugier, B., and E.A. Ripley: 1974. A sensitive device for recording atmospheric CO_2 profiles. J. Appl. Ecol. 11:103-110.

Spittlehouse, D.L., and T.A. Black: 1980. Evaluation of the Bowen ratio-energy balance method for determining forest evapotranspiration. Atmos. Ocean 13:98-116.

Stewart, J.B., and A.S. Thom: 1973. Energy budgets in pine forest. Quart. J. R. Meteor. Soc. 99:154-170.

Thom, A.S.: 1979. Momentum, mass and heat exchange of plant communities. pp. 57-110 in Vegetation and the Atmosphere, Vol. 1. ed. by J.L. Monteith. Academic Press, New York.

Thom, A.S., J.B. Stewart, H.R. Oliver, and J.M.C. Gash: 1975. Comparison of aerodynamic and energy budget estimates of fluxes over a pine forest. Quart. J. R. Meteor. Soc. 101:93-105.

Webb, E.K., G.I. Pearman, and R. Leuning: 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quart. J. R. Meteor. Soc. 106:85-100.