

COFFEE LEAF TEMPERATURES IN A TROPICAL ENVIRONMENT

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SUMMARY

Measurements of leaf temperature, air temperature, stomatal resistance and the net radiation of leaves are presented for coffee leaves exposed to the sun and shaded. Sunlit leaves were generally between 10°C and 15°C above air temperature (which was approximately 29°C) and shaded leaves were 1°C or 2°C below air temperature. Leaf temperatures are analysed in terms of the leaf energy balance equation and transpiration rates are calculated. Stomatal resistance of sunlit leaves was often higher than that of shaded leaves in continuous sunshine, however on days following substantial rain the stomata of sunlit leaves remained open. The affect of leaf temperatures on the dry matter production of coffee is briefly discussed.

1. INTRODUCTION

There is considerable evidence that the physiology of coffee is greatly affected by temperature. For example SUAREZ DE CASTRO & RODRIGUES (1956) noted that shoot growth rate increases at higher temperatures and BARROS & MAESTRI (1974) attributed a temporary decline in the growth of laterals in the growing season, to high temperatures. HEATH & ORCHARD (1957) first demonstrated an increase in the sub-stomatal CO₂ concentration of coffee leaves as the temperature increased, and suggested that this was the cause of midday closure of stomata. NUNES et al. (1968) confirmed that the sub-stomatal CO₂ concentration increases at temperatures above 24°C and suggested from their results that the net rate of dry matter production would approach zero at temperatures above 34°C.

Despite all this evidence showing the importance of leaf temperatures to the physiology of coffee, there are very few reports of leaf temperature measurements on coffee growing in the field, but ALVIM (1958) reported measuring temperatures of leaves exposed to full sunlight which were 20°C in excess of air temperature and CANNELL (1971) measured leaf temperatures of around 40°C in Kenya.

This paper reports leaf temperatures of coffee measured in the field and analyses the temperatures in terms of the leaf energy balance. The results given here are typical for the humid tropical environment encountered in the south of Bahia, Brazil, but can be used as a guide for many coffee growing regions where daytime air temperatures and radiation intensity are similar.

2. MATERIAL AND METHODS

Measurements were made at the Centro de Pesquisas do Cacau (CEPEC), Bahia, Brazil (latitude 15°S) in the centre of a small area of Robusta coffee trees (*Coffea canephora*, cultivar Guarini) with a 3 × 3 m planting pattern. On the south and west sides of this area are tall forest trees (shade trees for cocoa) and to the east other tree crops, all of which give good wind shelter to the coffee.

Initial measurements of leaf temperatures were made on 18 March 1976 using an infra-red thermometer (T.F.D.L., Wageningen, Netherlands) and subsequent measurements in May 1976 were made using 42 S.W.G. copper/constantan thermocouples. The thermocouples were arranged in two sets, each consisting of five pairs of junctions wired in series. One set was allocated to leaves on the west side, and the other set to leaves on the east side of the tree. Each measuring junction was attached to a leaf by threading the wires back and forth through the midrib three times, thus forming two loops which were pressed against the leaf lamina holding the junctions in contact with the underside of the leaf. Leaf to air temperature differences were measured directly by mounting the reference junctions of the thermocouples in an aspirated radiation shield of an Assmann psychrometer. The same Assmann psychrometer was used to measure air temperature. The output from each set of thermocouples was read separately using a microvoltmeter (Comark Ltd., England) and leaf and air temperatures were recorded at five-minute intervals during the measurement periods.

Measurements of stomatal resistance were made using a ventilated diffusion porometer (Cayuga Developments, U.S.A.). Leaves for these measurements were divided into two groups, sunlit and shaded leaves. Five leaves in each group were measured for each set of readings, choosing leaves at the third node from the terminal apices.

The net absorbed radiant energy for those leaves with attached thermocouples was measured with a miniature net radiometer (Solar Radiation Instruments, Australia); readings were made above, beneath and in the same plane as each leaf. Net radiation and stomatal resistance data were collected alternately.

Windspeed and humidity measurements were made on 19 May 1976. A sensitive cup anemometer (Sheppard type, Casella & Co. Ltd., England) was mounted at 1.5 m above the ground close to the tree on which measurements were being made, and run of wind was recorded at five minute intervals. Vapour pressure was recorded occasionally using an Assmann psychrometer and showed little variation during the day. Good agreement was obtained between the vapour pressure given by the Assmann psychrometer and the mean of 09.00 and 15.00 records from a nearby meteorological station. On other days therefore, vapour pressures obtained from the meteorological station are used in the analyses.

The weather conditions were similar on all measurement days. Windspeed

was light and bright sunshine prevailed, with occasional shadows cast by isolated cumulus clouds.

3. RESULTS

3.1. Leaf temperatures

Temperatures of leaves on the west and east sides of the tree recorded on 12, 19 and 27 May are shown in *figure 1*. The graph shows two distinct temperature bands for each set of leaves, representing conditions when leaves were exposed to the sun and when occasional cloud shaded the whole tree from direct solar radiation. In sun, the temperature of leaves on the east side reached a maximum of about 35°C at 11.00 and fell to below 30°C after about 14.00. On the west side however, the temperature rose rapidly until about 13.00, remaining above 40°C between 12.00 and 15.30. At 15.30, when a shadow was cast by the sun falling behind nearby forest trees, the leaf temperatures fell abruptly to about 26°C.

From 11.00 to 15.00 air temperature was usually between 28°C and 30°C. The leaf temperatures excess on the west side occasionally exceeded 15°C during this period, and was over 10°C almost continuously between 12.30 and 15.30. Leaves on the east side were cooler than the air from 13.30 onwards, the leaf-air temperature difference increasing to about -2°C at 15.00.

As the temperatures given here are the average for five leaves on each side of the tree, individual leaves will experience greater temperature extremes. Estimates were made of the percentage exposure to direct solar radiation for each set of leaves with attached thermocouples. Leaves were divided into three

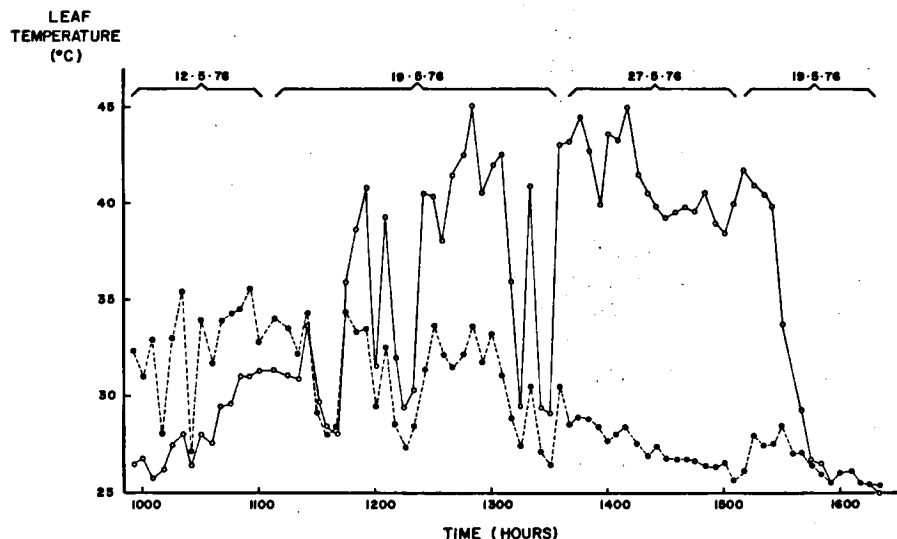


Fig. 1. Daily pattern of coffee leaf temperatures using data from three days in May 1976. Key: ●- - - ● East side, ○—○ West side.

Table 1. Temperatures of coffee leaves, 18 March 1976 (I. R. thermometer).

Time	Air temp. °C	Leaf temp. °C	δT_1 °C	
1243	30.0	27.3	-2.7	
1245	29.6	28.1	-1.5	Shaded
1250	29.6	27.0	-2.6	
1255	28.9	25.1	-3.8	
1312	30.5	38.7	8.2	
1508	31.4	46.3	14.9	Sunlit
1510	30.6	45.3	14.7	
1606	29.3	28.0	-1.3	
1608	28.9	27.5	-1.4	Shaded
1611	28.7	26.0	-2.7	
1613	28.6	27.4	-1.2	

categories: complete shade (0%), partial exposure (50%) and full exposure (100%). The average exposure for leaves on the east side was 70% at 11.00, falling to 40% at 13.00 and 10% at 15.00. The west side rose from 50% at 11.00, reaching 100% soon after 13.00 where it remained until 15.30. Leaves exposed to full sunlight in the morning would be several degrees higher than the average temperature shown in *figure 1* for the east side, where exposure to direct radiation was estimated at 70%. In the afternoon however, values presented for the west side are representative of leaves fully exposed to the sun.

Temperatures of individual, naturally oriented leaves were measured on 18 March using an infra-red thermometer. The results are given in *table 1* where the air temperature, leaf temperature and leaf to air temperature difference are shown for sunlit and shaded leaves.

The leaf to air temperature difference is generally between 10°C and 15°C for sunlit leaves and between -1°C and -3°C for shaded leaves. These values agree very well with the measurements made using thermocouples and confirm that the thermocouples were giving accurate leaf temperatures. Other work has shown that similar thermocouples may lead to an under-estimation of the leaf-air temperature difference by as much as 30% (BUTLER 1976, PIETERS & SCHURER 1973), because the thermocouple on the leaf surface protrudes significantly into the boundary layer. The boundary layer thickness of the coffee leaves referred to in this work would certainly have been greater than that for the apple leaves in previous work (BUTLER 1976) because the windspeed encountered here was generally less than 0.5 m s⁻¹ and coffee leaves are bigger. These factors may account for the good agreement found between the thermocouples and infra-red thermometer.

3.2. Net radiation

The daytime pattern of net radiation for leaves on the west and east sides of the tree is shown in *figure 2*. Each point on the graph is the average of measurements

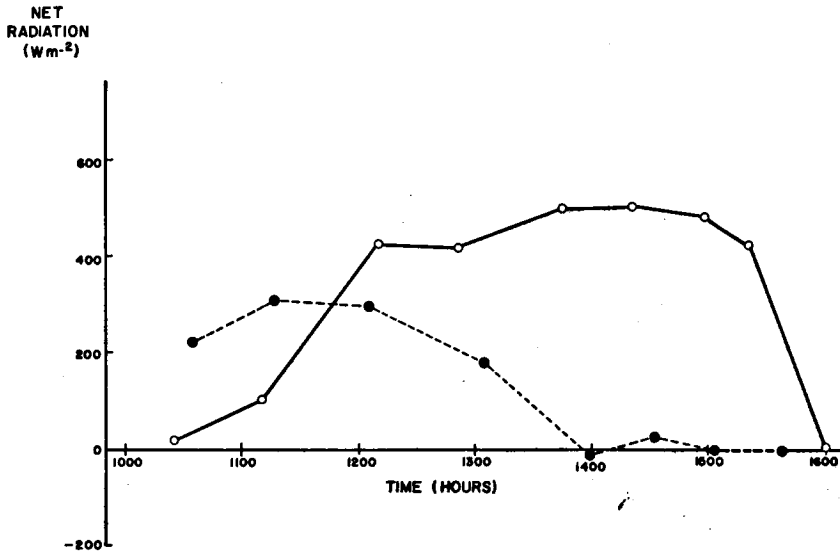


Fig. 2. Net radiation of coffee leaves, May 1976. Key: ○—○ West side ●---● East side.

above and below each of five leaves. Net radiation was not measured when the sun was obstructed by cloud, so the graph indicates values only when leaves were exposed to direct radiation. Radiation on the east side was at a maximum between 1100 and 1200, dropping to about zero after 1400. The maximum level of measured radiation for the east side was lower than that for the west side because the leaves of the former were only 70% exposed to direct solar radiation (see section on leaf temperatures). The level of net radiation for leaves on the west side rose sharply before noon and then remained approximately constant until 1530 when a shadow was cast by nearby trees. It is significant that most leaves on this coffee variety hang vertically so that the efficiency of radiation interception is greatest early and late in the day, when the intensity of direct radiation is relatively weak. This leads to a flat radiation absorption curve throughout the major part of the day.

The level of net radiation is the most important factor determining the difference between leaf and air temperatures. In *figure 3*, the leaf to air temperature difference, δT_1 , is plotted against the net radiation, R_n , absorbed by the leaves along with the linear regression

$$\delta T_1 = 0.0264R_n - 1.07 \quad (r = 0.916) \quad (1)$$

Values of net absorbed radiation as high as 650 W m^{-2} were observed on horizontally exposed leaves in the middle of the day, for which equation 1 predicts a leaf to air temperature difference of 16.0°C . This temperature difference is close to the figure of 20°C reported by ALVIM (1958) for a single

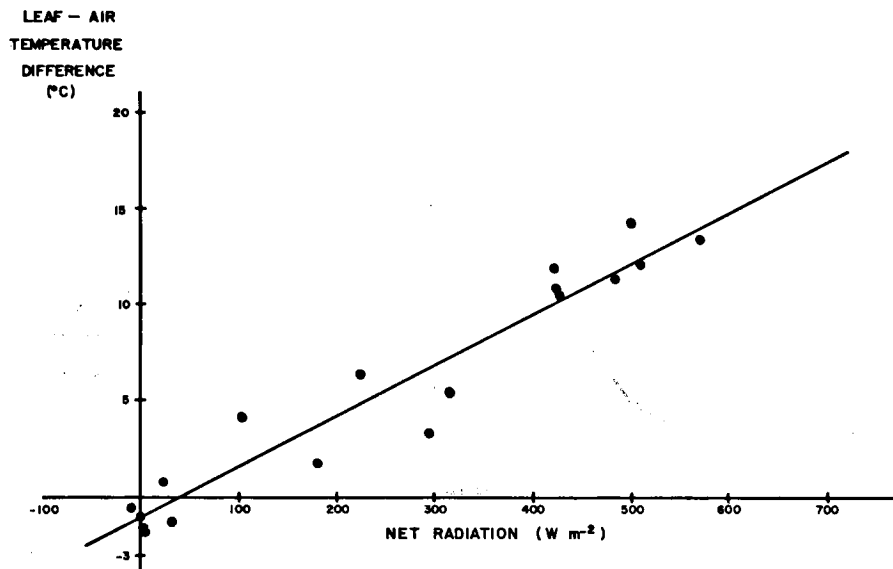


Fig. 3. Leaf-air temperature difference plotted against net radiation of coffee leaves.

horizontally exposed leaf. A figure of $20^{\circ}C$ could readily be achieved if the diffusive resistances to heat and mass transfer were somewhat larger than in this study.

3.3. Stomatal resistance

Porometer measurements on 18 March and 12, 17 and 19 May all showed a similar trend of stomatal resistance. During the morning, between 10.00 and 12.00, the resistance values of sunlit and shaded leaves were not significantly different from each other: the average value for all leaves during this period on 12 and 19 May was $650 s m^{-1}$.

On 18 March stomatal resistance measurements were begun at 12.20 when the sunlit leaves had an average stomatal resistance of $1470 s m^{-1}$, in comparison with an average value of $580 s m^{-1}$ on the shady side of the tree. Between 12.30 and 13.00 a large cloud covered the sun and, during this period, the stomata on the west side of the tree opened, showing an average value of $660 s m^{-1}$ immediately after the sun came out again, when the leaf temperature reached $38.7^{\circ}C$. Later in the afternoon at 15.15, both the sunlit and shaded leaves showed a similarly high stomatal resistance (1350 and $1650 s m^{-1}$ respectively).

On 17 May the sunlit leaves reached a very high value by 14.00 (an average of $2520 s m^{-1}$) which was significantly higher than the shaded leaves (average value $1080 s m^{-1}$) at a 1% probability level.

Measurements of 19 May showed that the stomatal resistance of shaded and

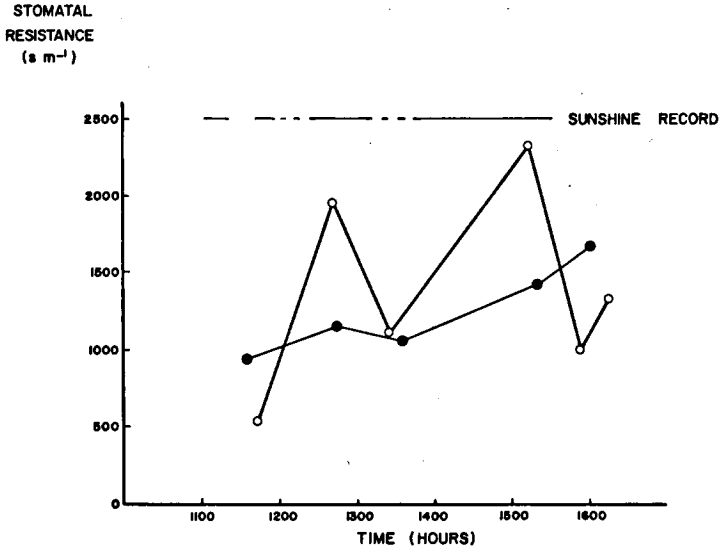


Fig. 4. Stomatal resistance of coffee leaves, 19 May 1976. Key: \circ sunlit leaves, \bullet shaded leaves.

sunlit leaves were equal in the late morning and again at 13.30 ($740\ s\ m^{-1}$ and $1190\ s\ m^{-1}$ respectively), when the sunshine was intermittent. During periods of continuous sunshine however, at 12.40 and 15.20 (see *figure 4*), the sunlit leaves had resistances significantly higher than those in the shade with probability levels of 5% and 1% respectively. After 16.00 when the tree was fully shaded, the stomata of leaves on the west side of the tree partially opened, resulting in a resistance highly significantly (probability level 0.1%) lower than the leaves which had been continuously shaded for several hours. The same effect was observed at the same time on 12 May.

The pattern of stomatal behaviour was quite different on 1 April and 28 May. Porometer measurements on 1 April (see *figure 5*) showed that the stomatal resistance of sunlit leaves remained fairly constant during the day (about $500\ s\ m^{-1}$) until the stomata closed abruptly at about 16.00.

On 28 May very thin, high cirrus clouds reduced the intensity of direct solar radiation. At 11.45 and 13.50 the resistances of all leaves were equal, but the sunlit leaves showed significantly lower resistances at 12.00 and 14.20 (the probability levels were 0.2% and 0.1% respectively). The absolute values of these resistances were $260\ s\ m^{-1}$ and $340\ s\ m^{-1}$, indicating that the stomata were almost fully open. On the second occasion, when the resistance was $340\ s\ m^{-1}$, leaf temperatures were observed for 15 minutes before measuring the stomatal resistance. The sunlit leaves remained between 34°C and 38°C , and the shaded leaves were between 27°C and 28°C .

These results indicate that, when leaves of coffee are exposed to continuous sunshine stomata usually close. This is in agreement with other observations

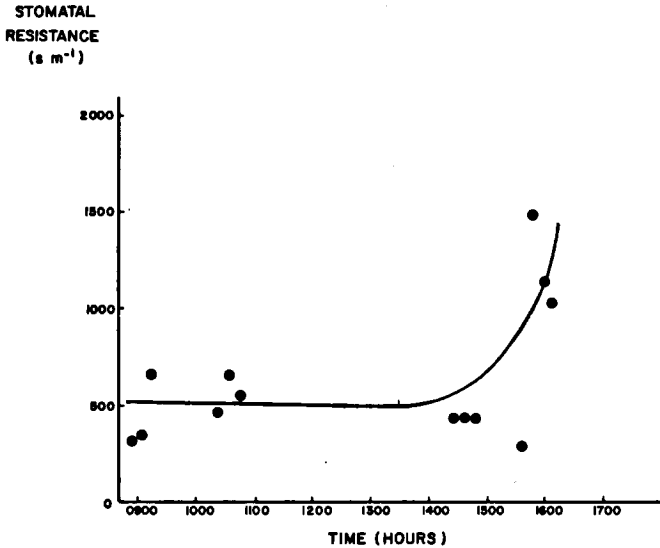


Fig. 5. Stomatal resistance of sunlit coffee leaves, 1 April 1976.

in the literature (for example NUTMAN 1937, ALVIM 1968 and ALVIM & HAVIS 1954). HEATH & ORCHARD (1957) first demonstrated that the intercellular space CO₂ concentration of coffee leaves increases with increasing temperature, especially above 30°C, and suggested that this caused midday closure of stomata. After sunlit leaves are shaded, the stomata partially open, resulting in a lower resistance than that for leaves which have been shaded for several hours.

The stomatal behaviour observed on 1 April and 28 May, however, suggests that stomatal closure does not always occur at temperatures above 30°C and, in fact, stomata can be almost fully open at about 36°C.

Soil moisture is known to be important to the stomatal behaviour of coffee (MAESTRI & VIEIRA 1958) and this may be a key to the two types of behaviour found here. The total rainfall during seven days before the day of measurements was 49, 2.9, 0.0 and 1.3 mm for 18 March, 12, 17 and 19 May respectively and 41.6 and 70.6 mm for 1 April and 28 May respectively. It is likely that there was little or no soil water stress on the days when the stomata of the sunlit leaves remained open.

3.4. Leaf energy balance and transpiration rates

The leaf energy balance can be described by the equation:

$$R_n = H + \lambda E \quad (2)$$

where R_n is the net flux of radiation to the leaf, H is the sensible heat flux from the leaf to the air and λE is the latent heat loss from the leaf in the transpiration

process. The units of all three variables are energy per unit time per unit plan area of leaf (W m^{-2}).

The sensible heat flux depends on the leaf to air temperature difference (δT_1), the size of the leaf and the windspeed, and is given by,

$$H = \frac{\rho c_p \delta T_1}{r_a} \quad (3)$$

where ρ is the density of dry air (g m^{-3}), c_p is the specific heat of air at constant pressure ($\text{J g}^{-1} \text{ } ^\circ\text{C}^{-1}$) and r_a is the boundary layer resistance to heat and mass transfer between the leaf and the air (s m^{-1}).

The latent heat flux depends on the difference in vapour pressure between the sub-stomatal cavities and the air, the stomatal resistance, the size of the leaf and the windspeed, and is given by,

$$\lambda E = \frac{\rho c_p (e_s(T_1) - e_a)}{\gamma (2r_a + r_s)} \quad (4)$$

where $e_s(T_1)$ is the saturated vapour pressure at leaf temperature (mb), e_a is the vapour pressure of the air (mb), γ is the psychrometric constant ($0.66 \text{ mb } ^\circ\text{C}^{-1}$) and r_s is the stomatal resistance (s m^{-1}). Since coffee leaves are hypostomatous, the boundary layer resistance to water vapour transfer is for one side of the leaf only, which is double the value for heat transfer (both sides of the leaf in parallel).

Measurements of net radiation, leaf and air temperature, vapour pressure and stomatal resistance are available, and it is normally possible to calculate the boundary layer resistance to heat and mass transfer from the windspeed and characteristic dimension of the leaves (for example LANDSBERG & POWELL 1973, MONTEITH 1965). The windspeed data recorded in the coffee plantation were all less than 0.5 m s^{-1} however, and the anemometer often stalled indicating windspeeds of less than 0.2 m s^{-1} . In these conditions, free convection would play an important role in the heat transfer process, especially when the leaf was much warmer than the air, so that an equation involving windspeed and the characteristic leaf dimension is not applicable in this case. However we can calculate the boundary layer resistance from the energy balance equation, since this is the only unknown parameter. All the components of the energy balance, using the average leaf temperature during the periods when radiation was being measured, are given for sunlit leaves in *table 2*.

The latent heat flux for sunlit leaves shown in *table 2*, ranges between 36 and 77 W m^{-2} which is equivalent to transpiration rates of 15 and $32 \text{ mg m}^{-2} \text{ s}^{-1}$. The maximum transpiration rate recorded was $62 \text{ mg m}^{-2} \text{ s}^{-1}$ on 28 May, when the leaf temperature was 36°C and the stomatal resistance 340 s m^{-1} .

Referring to *figure 3*, the regression line indicates that the net radiation was 40 W m^{-2} when the leaf and air temperatures were equal. In this case the sensible heat flux was zero, so the latent heat flux is equal to the net radiation

Table 2. Components of the leaf energy balance for sunlit leaves.

R_n ($W m^{-2}$)	δT_1 ($^{\circ}C$)	$e_s(T_1)$ (mb)	e_a (mb)	r_s ($s m^{-1}$)	H ($W m^{-2}$)	λE ($W m^{-2}$)	r_a ($s m^{-1}$)
422	11.9	85.0	26.0	1920	369	53	38
425	10.8	73.5	26.0	2370	389	36	33
209	4.4	49.0	24.0	500	132	77	39
223	6.3	51.0	24.0	760	166	57	45
420	10.8	76.5	25.5	2500	384	36	33
406	13.0	86.0	25.5	2500	364	42	42

($40 W m^{-2}$). The total resistance to water vapour transfer ($2r_a + r_s$) obtained from equation 4 is equal to $627 s m^{-1}$, indicating a stomatal resistance values of about $560 s m^{-1}$ (assuming that $r_a = 35 s m^{-1}$) which is in good agreement with the porometer measurements on shaded leaves. Shaded leaves are typically $2^{\circ}C$ cooler than the air (see *table 1*) and this would reduce the transpiration rate to about $30 W m^{-2}$ which is equivalent to $13 mg m^{-2} s^{-1}$.

Estimates have shown that about 50% of the leaves are exposed to direct radiation in sunny conditions so, giving equal weight to sunlit and shaded leaves, the average transpiration rate may vary between 15 and $40 mg m^{-2} s^{-1}$, depending on the stomatal aperture. The maximum value given by NUNES et al. (1968) for coffee grown in a glasshouse was $18 mg m^{-2} s^{-1}$.

4. DISCUSSION

The temperature of sunlit coffee leaves is generally between $10^{\circ}C$ and $15^{\circ}C$ above air temperature, while those leaves in the shade are between $1^{\circ}C$ and $3^{\circ}C$ below air temperature. When the air temperature is about $30^{\circ}C$ therefore, sunlit leaves are above $40^{\circ}C$ and shaded leaves are below $30^{\circ}C$.

NUNES et al. (1968) suggested that the rate of dry matter production of coffee would approach zero above $34^{\circ}C$. Certainly, if the trend they showed continues above $35^{\circ}C$, the internal CO_2 concentration of the leaves would approach 300 ppm at $40^{\circ}C$, a condition where no flux of CO_2 into the leaf would occur. However, it is not clear whether the temperature of $35^{\circ}C$ which they quoted refers to that of the air or of the leaf, and if it was in fact air temperature, the leaf could have been considerably hotter. Nevertheless their results indicate that coffee leaves work very inefficiently at temperatures above $40^{\circ}C$, yet sunlit leaves commonly reach such temperatures. Since about 50% of the leaves in a tree are exposed to the sun at any one time, the effective producing leaf area could be reduced by 50% in sunny conditions.

It seems probable however, that field plants without shade would adapt to the high temperatures encountered and behave differently to those cultivated in growth rooms. HUERTA (1954), ALVIM (1960) and CASTILLO (1961) showed that the net assimilation rate of coffee seedlings was higher in full

sunlight than in shade. HUXLEY (1967) compared the effect of shade on seedlings of Arabica and Robusta coffee and showed that the two varieties behaved similarly, however in agreement with other reports (MACHADO 1946, MAESTRI & GOMES 1961 and SUÁREZ DE CASTRO et al. 1962), he found a lower net assimilation rate in full sunlight than in partial shade. ALVIM (1960) used seedlings which were exposed to the sun before the cotyledons opened, suggesting that adaptation to high temperatures begins at a very early physiological stage.

Following substantial rain, the stomata of the sunlit leaves did not close in spite of temperatures well above 30°C. An exceptionally high CO₂ concentration in the sub-stomatal cavities would be expected to cause stomatal closure, so it appears that these leaves were behaving differently to those studied by HEATH & ORCHARD (1957) and NUNES et al. (1968). It is likely that this is a result of adaptation to field conditions, although a varietal difference may exist between Robusta coffee used in this work and Arabica coffee used by HEATH & ORCHARD (1957) and NUNES et al. (1968) in their experiments.

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REFERENCES

- ALVIM P. DE T. (1958): Recent advances in our knowledge of coffee trees. I - Physiology. *Coffee Tea Ind. Flavor Field* **81**: 17-25.
- (1960): Physiology of growth and flowering in coffee. *Coffee* (Turrialba, Costa Rica) **2**: 57-62.
- (1968): Some factors to be considered in diagnosing moisture deficiency by stomatal opening. *Ciência e Cultura* (São Paulo) **20**: 726-732.
- & J. R. HAVIS. (1954): An improved infiltration series for studying stomatal opening as illustrated with coffee. *Plant Physiol.* **29**: 97-98.
- BARROS, R. S. & M. MAESTRI, (1974): Influência dos fatores climáticos sobre a periodicidade de crescimento vegetativo do café (*Coffea arabica* L.). *Rev. Ceres* (Viçosa) **21**: 268-269.
- BUTLER, D. R. (1976): Estimation of the transpiration rate in an apple orchard from net radiation and vapour pressure deficit measurements. *Agric. Meteorol.* **16**: 277-289.
- CANNELL, M. G. R. (1971): Seasonal patterns of growth and development of Arabica coffee in Kenya. Part III. Changes in photosynthetic capacity of the trees. *Kenya Coffee* **36**: 68-74.
- CASTILLO, Z. J. (1961): Ensayo de analisis del crecimiento en café. *Cenicafé* (Colombia) **12**: 1-16.
- HEATH, O. V. S. & B. ORCHARD (1957): Midday closure of stomata. Temperature effects on the minimum intercellular space carbon dioxide concentration "Γ". *Nature* **180**: 180-181.
- HUERTA, S. A. (1954): La influencia de la intensidad de luz en la eficiencia asimilatoria y el crecimiento del cafeto. Turrialba, Instituto Interamericano de Ciencias Agrícolas. P. 69 (Unpublished Master's Thesis).
- HUXLEY, P. A. (1967): The effects of artificial shading on some growth characteristics of Arabica and Robusta coffee seedlings. I. The effects of shading on dry weight, leaf area and derived growth data. *J. appl. Ecol.* **4**: 291-308.

- LANDSBERG, J. J. & POWELL, D. B. B. (1973): Surface exchange characteristics of leaves subject to mutual interference. *Agric. Meteorol.* **12**: 169–184.
- MACHADO, A. (1946): Influencia del sombrio et suelo y los practicas de cultivo en el desarrollo del cafeto en sus premeros meses de vida propoa; experimento preliminar. *Bol. Inf. Cent. nac. Invest. Café* (Colombia) **1**: 1–32.
- MAESTRI, M. & F. R. GOMES (1961): Crescimento de mudas de café (*Coffea arabica* L. var. Bourbon) sob diferentes niveis de luz. *Rev. Ceres* (Viçosa) **11**: 265–271.
- & C. VIEIRA (1958): Movimento de estômatos em café sob condições naturais. *Rev. Ceres* (Viçosa) **10**: 324–331.
- MONTEITH, J. L. (1965): Evaporation and environment. In 'The state and movement of water in living organisms'. 19th. *Symp. Soc. exp. Biol.* p. 205.
- NUNES, M. A., J. F. BIERHUIZEN & C. PLOEGMAN (1968): Studies on the productivity of coffee. I. Effect of light, temperature and CO₂ concentration on photosynthesis of *Coffea arabica*. *Acta Bot. Neerl.* **17**: 93–102.
- NUTMAN, F. J. (1937): Studies on the physiology of *Coffea arabica*. II. Stomatal movements in relation to photosynthesis under natural conditions. *Ann. Bot.*, N.S. **1**: 681–693.
- PIETERS, G. A. & SCHURER, K. (1973): Leaf temperature measurements I. Thermocouples. *Acta Bot. Neerl.* **22**: 569–580.
- SUÁREZ DE CASTRO, F. & G. A. RODRIGUEZ (1956): Relaciones entre el crecimiento del cafeto y algunos factores climáticos. Federación de Cafeteros de Colombia, *Boletín Técnico* **16**: 13.
- , M. MORENO, L. MONTENEGRO & M. BOLAÑOS (1962): Influence of shade, organic matter and planting distances upon growth of coffee seedlings. *Coffee* (Turrialba, Costa Rica) **4**: 25–35.