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Solar radiation interception and its relation with transpiration in different coffee canopy layers

Interceptação da radiação solar e sua relação com a transpiração em diferentes extratos foliares de um cafeeiro

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Abstract - *Solar radiation distribution within a coffee plant and its effects on the transpiration rate at different plant layers were studied. Net radiation (Rn), photosynthetically active radiation (PAR) and sap flow (SF) were measured at three heights (0.2, 1.10, and 1.55 m above the ground) within a coffee tree during twenty days. It was observed that about 60% of the Rn and PAR incident on the plant were extinguished along the first layer. Extinction coefficient for Rn and PAR presented a trend of reduction through the plant. The relation between Rn, expressed per leaf area unit, and SF indicated a significant difference among plant layers. However, analysing the transpiraton rate per leaf area unit, there was a similarity between the plant layers, independent of their exposure to solar radiation. The different patterns of interaction between plant layers and radiant energy caused different ratios between absorbed energy and water lost, resulting that the intermediate and lowest layers had the highest efficiency in using the energy for transpiration.*

Key words*: sap flow, net radiation, photosynthetically active radiation, coffea arabica*

Resumo - *A distribuição da radiação solar em um cafeeiro e seus efeitos sobre a taxa de transpiração de diferentes camadas foliares foram estudados. Para tanto, mediu-se o saldo de radiação (Rn), a radiação fotossinteticamente ativa (PAR) e o fluxo de seiva (SF) em três alturas (0,2; 1,10 e 1,55m acima do solo) na copa de um cafeeiro adulto durante vinte dias. Observou-se que cerca de 60% de Rn e PAR que atingem a planta é extinta ao longo do primeiro extrato. O coeficiente de extinção apresentou uma expressiva tendência de redução ao longo da planta. A relação entre Rn, expressa em unidade de área foliar, e SF indicaram uma expressiva diferença entre os extratos foliares, havendo, entretanto, similaridade entre os extratos quando se avaliou a taxa de transpiração por unidade de área foliar. Os diferentes padrões de interação dos extratos foliares com a energia radiante resultaram em diferenças significativas na razão entre energia absorvida e perda d'água, sendo que os extratos intermediário e inferior tiveram maior eficiência no uso da energia para transpiração.*

Palavras-chave*: fluxo de seiva, saldo de radiação, radiação fotossinteticamente ativa, coffea arabica.*

Introduction

Plant transpiration and photosynthesis rates are mainly determined by the interception of solar radiation by the canopy, and several studies were carried out to characterize the radiation as a determinant factor of agricultural yield (AUBERTIN & PETER, 1961; YAO & SHAW, 1964; PENDLETON et al., 1966; SAKAMOTO & SHAW,

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1967), or just to characterize the solar radiation regime above and below the vegetation (PEREIRA et al., 1982; MACHADO et al., 1985).

These kinds of studies are more difficult for sparse crops, due the different types of geometry of orchards (spacing and arrangement of the trees) and also due to the canopy geometry. The few studies realized for sparse crops had focused only the quantitative aspect of the radiation, without the establishment of ecophysiological relationships (TURREL & AUSTIN, 1965; GREENE & GERBER, 1967; PALMER, 1977). NUTMAN (1937, 1941), tried to establish a relation between radiant energy and transpiration rate and also with stomatal closure of young coffee plants cultivated in vases and submitted to different radiative conditions, finding some relationships that could be applied to understand the performance of young coffee plants submitted to different amounts of radiation. However, for adult coffee plants in field conditions such relations were still not studied.

Therefore, due the few studies approaching this aspect in adult coffee plants, this work had the objective of quantifying the radiation intercepted in three layers of an adult coffee tree in a high density system, evaluating the variation of the extinction coefficient and available radiant energy (Rn_{ef}), and establishing the relationship between Rn_{ef} and transpiration rate in each layer and also for the whole canopy.

Material and Methods

The experiment was carried out in a non shaded irrigated coffee plantation (*Coffea arabica* L.), cultivar Mundo Novo Apuatã, at the Agricultural College "Luiz de Queiroz", University of São Paulo, Piracicaba, Brazil (Lat. 22°43' S, Long. 47°30' W, 560 m a.m.s.l.). Trees were four years old, spaced 2.5m x 1.0m (the direction of the hedgerows was N-S) and the total area was 2750 m². Management practices were done regularly, such as weed control, fertilizer application and phytosanitary control. The soil is classified as an Alfisol ("Terra Roxa Estruturada", series Luiz de Queiroz).

The experiment was performed from 17 April to 24 May, 2001, being thirty-three days used for solar radiation analysis, and twenty days for sap flow studies, as described below. One healthy plant was used, representing the average condition of the orchard, and it was about 1.8 m high, with a maximum canopy diameter of about 1.5 m (Figure 1). This plant received an extra amount of water (about 5 mm per day) to ensure its transpiration was at a maximum rate.

Net radiation (*Rn*) and photosynthetically active radiation (*PAR*) were measured at four levels above canopy, at 2.20 m above the ground, and within one tree, at 1.55, 1.10 and 0.20 m above the ground (Figure 1), using net radiometers (Q*7.1, REBS Inc.) and silicon photovoltaic detectors (LI190SB Quantum Sensor, Li-Cor, Inc.). The sensors height represented the following foliage layers: L_1, the top layer, above 1.55 m; L_2, between 1.10 and 1.55 m; and L_3, between 1.10 m and 0.20 m. At each every three days, the position of the Rn and PAR sensors in relation to the compass directions was altered to minimize the differences in amount of radiation between east and west faces of hedgerow.

To calculate the extinction coefficient (*k*) of each plant layer and for the whole plant, hourly averages of Rn and PAR were used when solar elevation was greater than 20° (PEREIRA et al.,

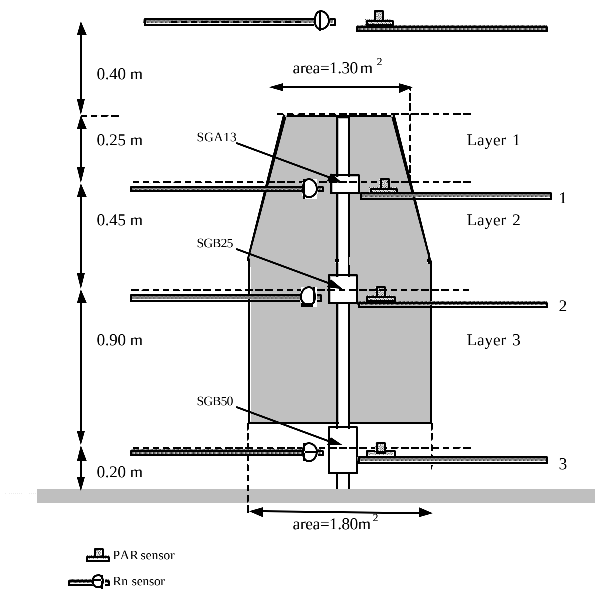

Figure 1 Schematic representation of the coffee plant studied and sensors location: sap flow sensors (SGB50, SGB25 e SGA13), *Rn* and *PAR* sensors, at positions 1, 2 and 3.

1982). For the L_1 (the highest layer), k was calculated using the measures taken above the layer, i.e., above the canopy, and below the layer. The same procedure was used for L_2 and L_3, and for the whole plant, when the measures at 2.20m and 0.20m were used. The following expression was applied to calculate k:

$$k = -\frac{ln\left(\frac{R_b}{R_a}\right)}{LAI} \quad (1)$$

where k is the extinction coefficient of the three layers, or the whole tree (dimensionless), R_b is the radiation measured below the layer, or below the tree (W m^{-2}), R_a is the radiation measured above the layer, or above the tree (W m^{-2}), and LAI is the leaf area index (m^2 m^{-2}) of the layer or plant. Radiation measurements used in eq. 1 were either Rn or PAR, and therefore k was calculated for both Rn and PAR. Although k for Rn is not usually calculated, it was used here to obtain a relation between transpiration and available radiant energy, and as certain similarity between k for net and incoming solar radiation may be expected, such values become useful.

To estimate the energy available at each layer per leaf area unit, the net radiation was expressed in terms of leaf area and then was called effective net radiation, calculated by:

$$Rn_{ef} = \frac{Rn_a - Rn_b}{LAI} \quad (2)$$

where Rn_{ef} is the effective net radiation (MJ m$^{-2}_{leaf}$ day^{-1}).

The leaf area was determined by counting all leaves (N) of each layer and measuring the width (i, m) and length (L, m) of 15% of them. The following equation was used to calculate the total leaf area of each layer:

$$LA = i\ L\ N\ F \quad (3)$$

where LA is the leaf area of the layer (m^2) and F is a coefficient that converts the product between the individual longest length (L) and width (i) to individual leaf area (LA_l). F was obtained from a linear regression analysis between the LA_l measured in an area meter (LI3100 Area Meter, Li-Cor Inc.) and the product L x i of 50 leaves randomly selected from the same plant where PAR and Rn measurements were done. Was obtained F = 0.703 (R^2 = 0.99). For the whole plant, LA was the sum of areas of each layer. The LAI of each layer was calculated using the projected area of its base (Table 1).

Assuming the sap flow integrated for 24 h as a good approximation of the daily transpiration (T) at each plant layer (VALANCOGNE & NARS, 1993; TREJO-CHANDIA et al., 1997), the sap flow (SF) was measured using commercial sensors (SGB50, SGB25 and SBA13, Dynamax Inc.), installed at 1.55m, 1.10m and 0.20m above the ground (Figure 1). The power supply dissipated ranged from 0.2 to 2 W, as a continuous current, depending on the sensor specification. Sap flow values were calculated according to the general heat balance equation (SAKURATANI, 1981; BAKER & VAN BAVEL, 1987), following the procedure proposed by VALANCOGNE & NASR (1993), and accumulated for 24 h, as follow:

$$SF = \frac{P - q_a - q_r}{cp\ dt} \quad (4)$$

where SF is the sap flow (g s^{-1}), P is the power applied to the sensor (W), q_a is the heat flux conducted vertically in the trunk (W), q_r is the heat flux conducted radially in the trunk (W), cp is the specific heat of water (4.186 J g^{1} °C^{-1}), and dt is the sap temperature increment along the sensor (°C).

Four sheets of aluminized paper were used for thermal insulation and a flexible silicon layer was used between the thermal insulation and the trunk to minimize moisture effects on the measurements. The electrical signals from the sensors were sampled every 10 s, and averaged every 15 min and stored in a datalogger (CR10X, Campbell Scientific Inc.) connected with a multiplexer board (AM416, Campbell Scientific Inc.). Data were analysed using descriptive statistics and linear regression.

Table 1. Leaf area (LA) and leaf area index (LAI) for each layer and for the whole coffee plant.

	LA (m^2)	LAI (m^2.m^{-2})
L_1	1.53	1.15
L_2	5.19	2.94
L_3	8.65	4.89
Plant	15.37	5.29

Results and discussion

Solar radiation measured above the plant (at 2.20 m above the ground) indicated clear skies during the measurements period with *Rn* values at 12:00 reached 400 W m^{-2} and *PAR* reached values as high as 300 W m^{-2}. *Rn* during the experiment was around 10 MJ m^{-2} day^{-1}, while *PAR* reached an average of 7.1 MJ m^{2} day^{-1}. About 60% of the Rn and *PAR* reaching the plant were extinct in L_1 (Figure 2), in spite of larger variability of the measures at 1.55m when compared to others heights, what was probably due the little leaf area of L_1 leading to direct sun exposure of the net radiometer sensor.

The extinction coefficient at each layer presented large variability within coffee plant (Table 2), witch occurred mainly in the first layer due to problems with *Rn* measurements mentioned above. The *k* values for *Rn* decreased from the top to the bottom of the canopy while for *PAR* was observed an irregular variation of k through the canopy. For whole plant, *Rn* showed a lower value of *k* than *PAR*, since *Rn* remaining close to 10 W m^{2} below the canopy while *PAR* tended to zero in this position, probably because the low extinction of infrared short wave component of *Rn* by foliage (ROSS, 1975; PEREIRA et al., 1982).

By relating Rn_{ef} and *SF* is possible to make inferences about the amount of radiant energy needed by the plant to transpirate 1 liter of water, and also to understand the influence of radiation on the water balance of the coffee plant and on the conditions for stomatal regulation of gas exchange. The ratio between *SF* and Rn_{ef} indicated a difference among foliage layers, ranged from 0.09 L.MJ^{-1} in L1, to 5.66 L.MJ^{-1} in L_3 (Figure 3). This large difference showed the importance of the upper layer in keeping the whole plant water balance, by absorbing most of the solar radiation, allowing the others foliage layers keep a more efficient synthesis of carbohidrate along the day, as the plant water conditions are more adequate for stomatal opening (NUTMAN, 1937; CANNEL, 1985).

The ratio between *SF* and Rn_{ef} for the whole canopy was similar to L_2 (Figure 4), with an average value of 0.47 L.MJ^{-1}. Although this SF/Rn_{ef} value is also dependent on others environmental variables, linear regression analisys between *SF* and Rn_{ef} had an R^2 = 0.45. This R^2 value indicates that water consumption of coffee plants can be estimated using meteorological variables, if the plant leaf area is known.

The transpiration rate in L_3 represented 60% of the total amount transpired by the plant (Figure 5A). The slope of the regression lines on Figure 5A agreed very well with the ratio of the leaf area at each layer to the total leaf area (Table 1), indicating that there was a similarity among layers transpiration rate, independent of their exposure to solar radiation (Figure 5B).

On leaf area basis, the transpiration rate of L_1 tended to be larger than transpiration rate of L_2 and L_3, but all layers presented a high variability, making it difficult to find differences among them (Figure 5B). The limited amount of radiant energy and the presumable similarity of air temperature and humidity

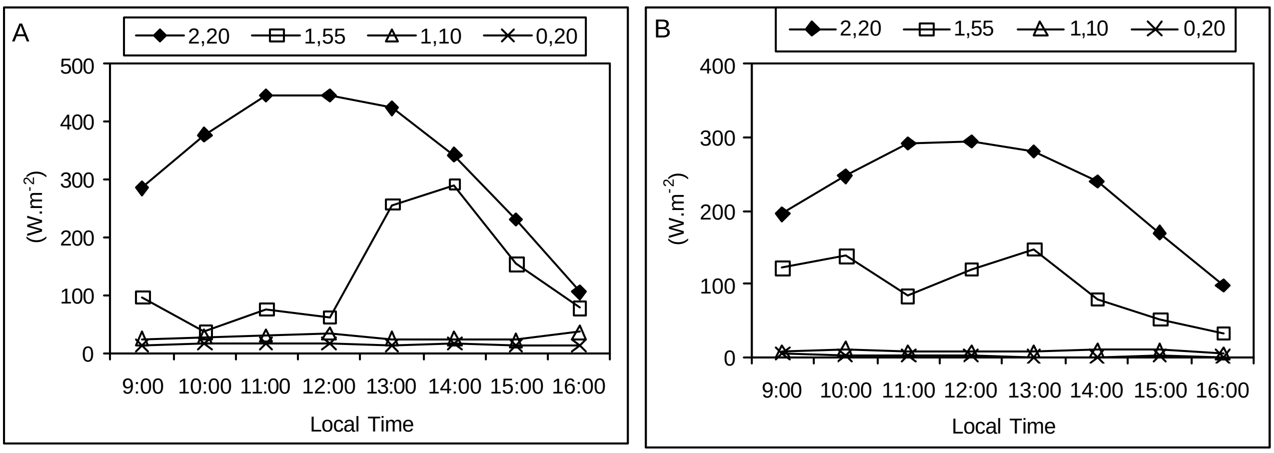

Figure 2. Average day-time fluctuation of: *Rn* (A), and *PAR* (B), measured above the canopy (2.2 m above the ground), and within the coffee canopy, at 1.55 m (bottom of L_1), at 1.10 m (bottom of L_2) and at 0.20 m (bottom of L_3).

Rev. Bras. Agrometeorologia, v. 11, n. 1, p. 1-6, 2003

Table 2 Average daily extinction coefficient (*k*) of coffee for net radiation (*Rn*) and photosyntetically active radiation (*PAR*), at each plant layer, and for the whole cofee plant. Number in brackets are standard deviation of the mean.

	Rn	*PAR*
L_1	0.92 [0.74]	0.79 [0.26]
L_2	0.44 [0.28]	0.82 [0.15]
L_3	0.11 [0.03]	0.32 [0.11]
Plant	0.55 [0.08]	0.93 [0.12]

conditions may explain the similiar transpiration rates of L_2 and L_3. However, in spite of the large amount of radiant energy absorbed by L_1, its transpiration rate was close to the transpiration of the others layers, and this may be a consequence of stomatal closure.

Similar results were presented by NUTMAN (1941), indicating the plant ability of keeping their stomatal open, even at low radiation levels, and reduce the water vapour lost when the conditions induce high transpiration rates. It was observed that, on the average, the sum of Rn_{ef} at L_2 and L_3 represented 15% of the available energy at L_1, while transpiration rates at these layers were about 80% of the one at L_1.

When all data were pooled, the regression line had a slope close to unity (1.04), differently from the values obtained when each layer were analysed separately (1.24 for L_1, 0.72 for L_2 and 1.06 for L_3). Linear regression analysis indicated that there is no statistical significance (10% level) when comparing layers versus canopy transpiration, which lays emphasis in the inference about stomatal regulation of water vapour loss.

Conclusions

Coffee tree layers have different available amounts of *PAR* and *Rn*, which lead the upper layer of leaves having the largest values of *k* and available energy. However, transpiration rates are not statisticaly different among layers, indicating that the upper layer has the highest resistance to vapour transfer to atmosphere, while the other two leaf layers are more efficient in using energy for transpiration.

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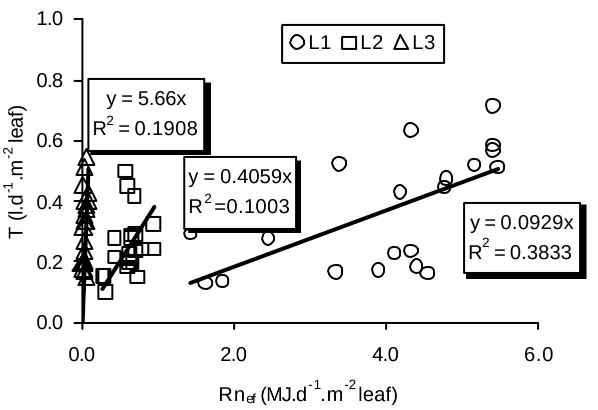

Figure 3. Relationship between coffee tree transpiration (*T*) and effective net radiation (Rn_{ef}) at each layer of coffee plant.

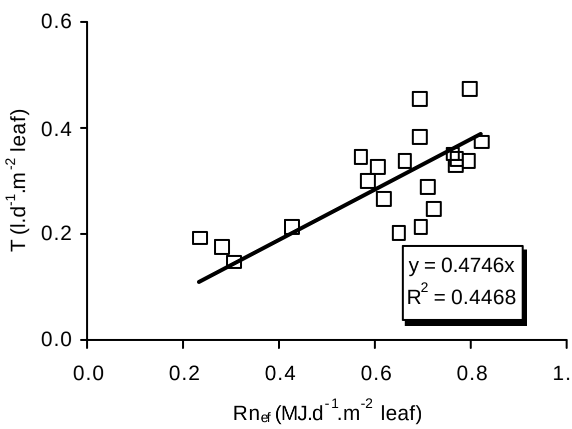

Figure 4. Relationship between transpiration (*T*) and effective net radiation (Rn_{ef}) for the whole coffee canopy.

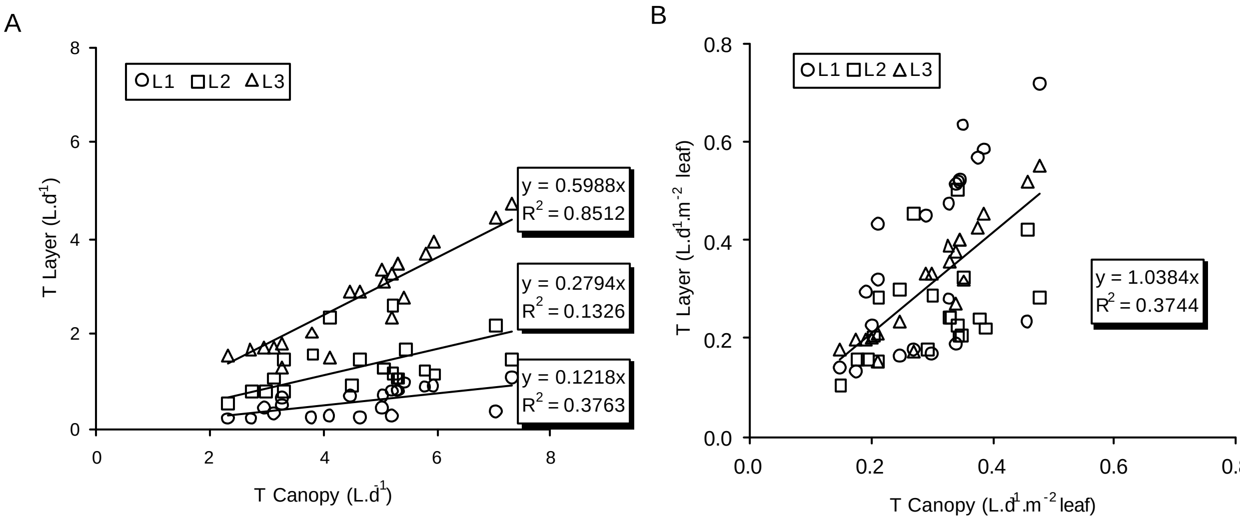

Figure 5. Relationship between the coffee canopy transpiration (T_{canopy}) and the transpiration at three layers of the coffee canopy (T_{layer}): A. transpiration on a volume basis; B. transpiration on a leaf area basis.

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