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Estimating maximum transpiration of coffee plants in high density population using Penman-Monteith model[1]

Estimativa da transpiração máxima de cafeeiros em plantio adensado com o modelo de Penman-Monteith

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Abstract - *The objective of this paper is to apply the Penman-Monteith model to estimate maximum transpiration (T) of four coffee plants with different leaf areas (LA), and to compare the data with sap flow measurements, obtained by the stem heat balance method. Aerodynamic resistance was estimated by Landsberg & Powell model and the values obtained throughout the experiment ranged from 23.5 to 37.5 s m^{-1}. The model used to estimate leaf resistance showed a reasonable agreement with mean hourly porometric data. Radiant energy absorbed by coffee canopies (Rnl) were measured with a mobile system that sampled four coffee plants simultaneously. Comparing estimated transpiration with sap flow data it was verified a good agreement for two of the four plants analyzed, with intermediate leaf area (9.3 and 11.4 m^2). The T of the plant with the smallest leaf area underestimated sap flow in about 30%, while the T of the plant with greatest leaf area overestimated sap flow in about 60%. These inverse trends were attributed to the use of only one relationship between LA and Rnl for the four plants rather than specific relationships for each one. These trends also suggests that there are not a linear relation between LA and Rnl, but in fact a nonlinear relationship that maximize Rnl in plants with low LA and minimize Rnl in plants with high LA. Comparing T estimates with Penman-Monteith model for all the plants together (LA=40.6m^2) with the sum of sap flow data measured in the four coffee plants a good agreement was verified, confirming that discrepancies verified for individual plants were mainly due to the Rnl measurements.*

Key words: *sap flow, aerodynamic resistance, leaf resistance, absorbed radiation, net radiation*

Resumo - *Neste trabalho, o objetivo é aplicar-se o modelo de Penman-Monteith para estimativa da transpiração máxima (T) de quatro cafeeiros com diferentes áreas foliares (AF) e comparar os dados com medidas de fluxo de seiva pelo método do balanço de calor. Para tanto, a resistência aerodinâmica foi estimada pelo método de Landsberg & Powell e os valores obtidos por este modelo ao longo do experimento variaram de 23,5 a 37,5 s m^{-1}. O modelo utilizado para estimativa da resistência foliar à difusão de vapor mostrou um nível de ajuste razoável em comparação com dados porométricos horários. A energia radiante absorvida pela copa dos cafeeiros (Rnl) foi medida com um sistema móvel que amostrava as quatro plantas simultaneamente. Comparando os valores de T estimada com dados de fluxo de seiva, verificou-se um bom nível de ajuste para duas das quatro plantas analisadas, com valores intermediários de AF (9,3 e 11,4 m^2). Para a planta com a menor AF, os valores de T subestimaram o fluxo de seiva em aproximadamente 30%, enquanto que na planta com maior área foliar, T superestimou o fluxo de seiva em aproximadamente 60%. Essas tendências inversas foram atribuídas ao uso de uma única relação entre AF e Rnl para as quatro plantas, ao invés de relações específicas para cada uma delas. Essas tendências inversas sugerem também que a relação entre AF e Rnl não é linear, mas sim uma relação que maximiza Rnl em plantas com baixa AF e minimiza Rnl em plantas com a AF elevada. Comparando as estimativas de T com o modelo de Penman-Monteith para os quatro cafeeiros (AF=40,6m^2) com a soma do fluxo de seiva, verificou-se um bom nível de concordância entre os dados, confirmando que as discrepâncias verificadas nas análises individuais foram devidas, principalmente, às medidas de Rnl.*

Palavras-chave: *fluxo de seiva, resistência aerodinâmica, resistência foliar, radiação absorvida, saldo de radiação*

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Introdution

Coffee plantations are distributed from Hawaii (25° N) to Paraná State in Brazil (24° S) (CARR, 2001). In Brazil, coffee has a historical economic and social importance, being one of the most important agricultural crops of the country. In the last years, coffee plantations has entered in regions where is possible to get high yields and to improve drink quality, but in most of these areas irrigation is essential to assure the economic viability of coffee crop.

For efficient water management of irrigation it is necessary to know the crop water requirement, which is controlled by factors related to the plant, the agricultural system, and the environment. Plant transpiration can be estimated with Penman-Monteith (PM) model (MONTEITH, 1965) if its inputs could be adequately adapted to the crop. This model is interesting because it allows the study of some eco-physiological crop aspects and at the same time it has practical applications, specially where drip systems of irrigation are used, where interrow evapotranspiration is not so important.

However, to use the PM model it is necessary to determine the input variables of the model, such as: absorbed net radiation by plants, leaf and aerodynamic resistance. The absorbed net radiation is one the most difficult and limiting tasks in estimating plant transpiration (PEREIRA et al., 2002). There are several works about leaf resistance modelling as much for annual as for perennial cultures that showed good results in relation to measured rl data (e.g. THORPE et al., 1980; SYVERTSEN & LLOYD, 1991; YU et al., 1998). In some cases, however, rl variations have been found poorly related to environmental variables (e.g. COHEN & COHEN, 1983; COHEN et al., 1993; MARIN, 1998; MARIN & ANGELOCCI, 1999) and this is an important variable in the PM model computation that remains to be better understood, specially for luxurious foliar development, such as coffee. The LANDSBERG & POWELL (1973) model is the most used tool to estimate the aerodynamic resistance for isolated plants, but is still difficult to know the limitations of this model for crops cultivated in hedgerows systems. Before entering in PM model calculation, each one of these input variables must be analyzed separately and, if possible, it must be validated with independent data.

Taking in account these considerations and the lack of information on the water consumption by coffee plantations in Brazil, the objective of this paper is to apply Penman-Monteith model to estimate the maximum transpiration of five-year coffee plants in Southeast Brazil.

Material and methods

The experiment was carried out between 10 August and 20 October in 2002 in 0.25 ha coffee plantation (*Coffea arabica*, var. Mundo Novo grafted on stock *Coffea canephora* var. Apoatã) in Piracicaba, State of São Paulo, Brazil (22°42’ S; 47°30’00’’ W; 546 a.m.s.l.). The coffee plants were planted in 1997 in north-south rows, 2.5m apart and with 1.0m within-row spacing, creating a compact hedgerow 2.5m height and 1.6m wide. The soil is classified as a Typic Rhodustults. The irrigation was made using a drip system to assure maximum transpiration by coffee plants.

A net radiometer (NR Lite, Kipp & Zonen) was placed at 4m above the ground and over the plant crown-interrow interface. Dry and wet bulb ventilated copper-constantan thermocouple psychrometer (MARIN et al., 2001a) were placed at 1.5m above the ground in the middle row of area. The grass net radiation (NR Lite, Kipp & Zonen) was measured at a nearby weather station.

Sap flow measurements were made with commercial sensors (SGB50 and SGB35, Dynamax) based on the heat balance method (SAKURATANI, 1981; BAKER & VAN BAVEL, 1987). Sensors were installed following recommendations of GUTIÉRREZ et al. (1994) regarding the thermal environmental effects on measurements, beyond all instructions of the manufacturer. For both micrometeorological and sap flow sensors, all electrical signals generated were measured by a CR7 datalogger at every 10s, computing automatically 15-min averages.

Penman-Monteith model was used to estimate the maximum transpiration of coffee plants, adapting it to hypostomatous leaves and with 15-min as:

$$T = LA \frac{s\ Rnl + 900\ \rho\ cp\ \dfrac{\Delta e}{ra}}{\lambda\left[s + \gamma\left(2 + \dfrac{rl}{ra}\right)\right]} \qquad (1)$$

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where T is the maximum transpiration (kg plant^{-1} 15min^{-1}); LA is the leaf area (m^2); Rnl is absorbed net radiation (MJ m^2 of LA 15min^{-1}); ra is the aerodynamic resistance (s m^{-1}); rl is the leaf resistance to vapour diffusion (s m^{-1}); ρ is the air density (kg m^{-3}); cp is the specific heat of dry air (J kg^{-1} K^{-1}); λ is the latent heat of water (MJ kg^{-1}); γ is the psychrometric coefficient (kPa °C^{-1}); Δe is the air vapour pressure deficit (kPa); s is the slope of the saturation vapour pressure curve with respect to temperature (kPa °C^{-1}). The estimated data were integrated for 24-hour, considering Rnl values equal to zero during the night.

Rnl was measured with a mobile system in which were connected eight net radiometers (Q7.1, REBS) (Figure 1). These sensors were installed in a circular aluminum arc, at 45º intervals in relation to center of the arc and positioned around the coffee hedgerow. The mobile system moved along the plant row direction with speed of 12.8m min^{-1}, over a support and pulled by a chain with 4.28m of length and set in motion by electric engine. The system described a full cycle (goes on and comes back) to each 40s, managed by a mechanism to reverse engine rotation in both extremities (MARIN, 2003). The system sampled the whole canopies of four coffee trees.

Rnl values were obtained by integration of measures of eight net-radiometers measuring equivalent areas. The sum of areas of the eight sensors composed the lateral surface of an hypothetical cylinder (excepting the plain area of two bases). The Rnl values were compared with horizontal measures of net radiation over grass (Rng) and global solar radiation (Rg), establishing relations between them to simplify the Rnl estimation. Rnl was calculated with the Equation (2):

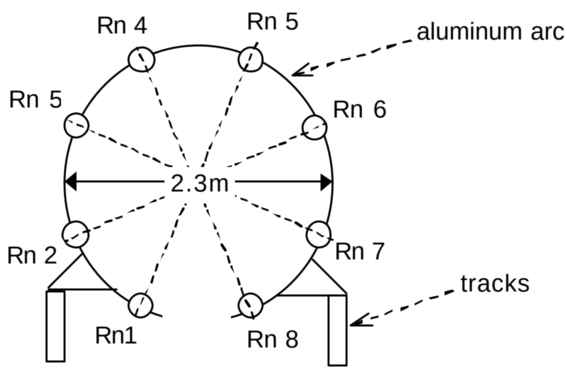

Figure 1. Schematic representation of the frontal view of the mobile system to radiant energy absorbed

$$Rnf = \frac{\left(\frac{1}{8}\sum_{i=1}^{8} Rn_i\right) d_h \ 2 \ R \ p}{AF} \qquad (2)$$

where Rn_i is the net radiation measurement of each net radiometer; d_h is horizontal distance covered by mobile system (4.28m) and; R is the radium of aluminum arc where net radiometers were fixed (1.15m).

The inferior part of the mobile system was painted on black to reduce the reflection of beam solar radiation. This procedure was adopted after some measurements days carried out over grass, when it was evidenced that main component error was solar radiation reflection. Alignment of net radiometers was made by focusing it to the geometric center of the aluminum arc of mobile system. Thus, the sensor plate of one net radiometer were aligned in comparison of its complementary sensor (opposite to it) using a flexible fine wire strained forming a 90º angle with sensor plate.

Aerodynamic resistance of coffee plants was estimated by Landsberg & Powell model with Equation (3):

$$ra = 58\sigma^{0.56}\left(\frac{\delta}{u}\right)^{0.5} \qquad (3)$$

where δ (m) is a leaf dimension; σ is a measure of foliage density given by the ratio of leaf area to the frontal (silhouette) area of coffee plant, and u is wind speed (m s^{-1}). Wind speed were measured with an anemometer (OA14, Met-One, starting speed = 0.45 m s^{-1}) at the middle of coffee canopy height (1.5m) as suggested by LANDSBERG & JONES (1981).

LA values for each plant were determined by two methods. For the first method all leaves of four plants were counted and multiplied by mean leaf area (MFA). MFA was obtained from Equation (4):

$$MFA = L \ W \ F \qquad (4)$$

where L is the greatest length and W the greatest width of 10% of total leaves of each coffee plant. F was obtained from a linear regression analysis between the individual leaf area measured in an area meter (LI3100 Area Meter, Li-Cor Inc.) and the product between the greatest length (L) and greatest width (W) of 50 leaves randomly selected from coffee plants studied. The value obtained for F was 0.703 (R^2 = 0.99) (MARIN et al., 2003).

The second method used to estimate LA was based on measurements of LAI-2000 Canopy Analyzer (Li-Cor, Inc). The mean value of LA was obtained by the arithmetic average between LA determined by the two methods, and it was considered as reference and was used in all calculations here. Table 1 presents the σ, LA and leaf area index (LAI) for the four coffee plants studied. The LAI of each plant was calculated using the projected area of its base.

The leaf resistance (r_l) was estimated following the approach of MARIN et al. (2001b), presented in Equation (5):

$$r_l = \frac{\rho\ cp\ \Delta e}{\gamma\ 0.70\ Rnl} - 2ra \quad (5)$$

The r_l estimates with the Equation (5) was made using Rnl calculated from relations between mobile system measurements and global solar radiation for 15-min interval. During the night, when the Equation (5) supplied with negative values, rl was considered equal the 10000 s m^{-1} (NOBEL, 1999) to simulate the cuticular resistance when occur the stomatal closure.

Estimated rl values were compared with porometric measurements made with Li1600 Steady State Porometer, Li-Cor, throughout five days. In each day, seven sequences of measurements were taken at intervals of 1 hour, sampling 20 leaves in each sequence. These 20 leaves were selected subdividing the canopy in three layers and two faces (east and west). Because the east face had more leaves than west one, 12 leaves were measured in east face and 8 in the west one.

Results and discussion

There are several works about r_l (or g_l) modeling made as much for annual as for perennial cultures. The results of them have showed good results in relation to measured rl data (e.g. THORPE et al., 1980; SYVERTSEN & LLOYD, 1994; YU et al., 1998). However, in some cases rl variations have been found poorly related to environmental variables (COHEN & COHEN, 1983) and both Syvertsen & Lloyd and Thorpe approaches explained less than 11% of these variations in orange hedgerows (COHEN et al., 1997) and acid lime (MARIN, 1998; MARIN & ANGELOCCI, 1999). For r_l coffee data obtained here, these two models explained no more than 20% of rl variation in relation to Δe and photosynthetically photon lux density (PPFD) (data not showed).

Figure 2 shows the relationship between measured and estimated r_l data using the approach of MARIN et al. (2001b). In acid lime this model also had better performance than Syvertsen & Lloyd and Thorpe approaches, and seems to be adequate specially when one need to know mean r_l values of plant stands with high r_l variability (MARIN et al., 2001b). High r_l variability in the same plant is mainly caused by changes in radiation, humidity and wind speed regimes leaf to leaf, which is normally found on tree canopies like coffee and citrus. Regression analyses for r_l and g_l data were significant at 1% of probability and the linear coefficient value does not have statistical significance at 5%, by T test.

Low levels of correlation verified with the model used here (Eq. 5) may be partially caused by few leaves sampled with porometric measurements what implies in uncertainties about the validation of the estimated data. To constitute a representative mean r_l value of coffee canopy one should sampled at least 94 from 4800 leaves of coffee plant studied. Although take this number of porometric data is operationally

Table 1. Measured values of leaf area (LA) with canopy analyzer (LAI2000) and by counting and measuring leaves (counting); mean leaf area index calculated and ratio between leaf area and silhouette of coffee plants (σ). Leaf area index was calculated in basis of projected canopy area on the soil surface.

	Plant 1			Plant 2			Plant 3			Plant 4		
Method	LA (m^2)	LAI	σ	LA (m^2)	LAI	σ	LA (m^2)	LAI	σ	LA (m^2)	LAI	σ
LAI2000	9.1			13.8			11.6			6.1		
Counting	9.6			14.0			11.1			5.9		
Average	9.3	3.6	3.2	13.9	4.5	4.2	11.4	3.4	3.1	6.0	2.4	2.0

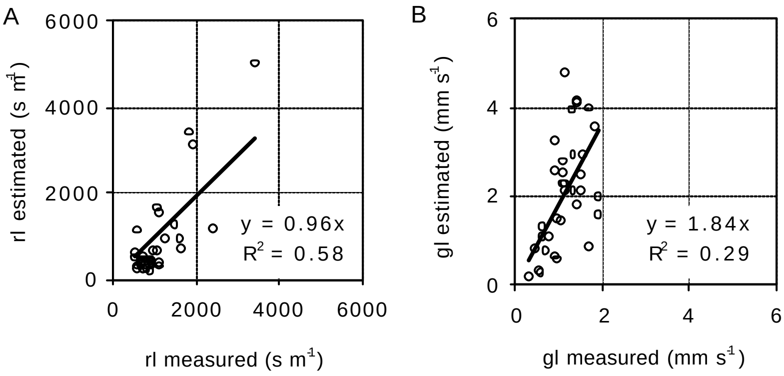

Figure 2. Relationship between estimated and measured mean hourly leaf resistances (rl) (A) and leaf conductance (gl) (B).

impracticable, this limitation in rl measurements must be considered in evaluation of models for estimate mean canopy r_l values.

The general average of gl measurements was equal to 1.19 mm s^{-1} (r_l = 840 s m^{-1}) and standard deviation of 0.69 mm s^{-1}. Table 2 shows the diurnal averages values g_l and the standard deviation for each day of measurement. The high coefficients of variation (CV) like in days 289 and 297 indicate the difficulties to obtain a mean canopy gl (or rl) value.

The average values ra obtained in this study ranged from 23.5 s m^{-1}, for plant 4 (LA=6.0 m^2), to 37.5 s m^{-1}, for plant 2 (LA=13.9 m^2). The small amplitude variation of ra values is due partially to low wind speed inside coffee plantation and partially to low model sensitivity to wind speed and plant parameters. The ra values obtained here are close to that verified in high density orange orchard (KALMA & FUCHS, 1976) and for acid lime orchard with high planting spacing (MARIN, 2000).

Landsberg & Powell model considers the mutual interference between leaves in isolated plants. Although it has been applied in crops constituting hedgerows (CASPARI et al., 1993; GREEN, 1993; ANGELOCCI, 1996; GREEN & MCNAUGHTON, 1997) one must consider that this arrangement differs from the conditions of Landsberg & Powell experiment, since mutual interaction between leaves tends to increase with the rise in the leaf density. So, it may be expected that ra values supplied by Landsberg & Powell model were less than hypothetical real values that should occur in high densities coffee plantations such as the studied here.

The correlation between measured Rnl data and Rng and Rg are presented in Figure 3 and the fitted equations indicates the possibility of modeling Rnl based on canopy parameters and solar radiation. However, here was only used the simple relations obtained with Rng and incoming solar radiation (Rg). Further works are been made to develop a model for coffee and other important crops in Brazil (ANGELOCCI et al., 2003). The differences between four coffee plants can not be evaluated because mobile system is not able to evaluate isolated plants. In spite of this, one can infer there are differences between four plants of coffee selected due to LA variations (MARIN et al., 2003).

Although Δe is an important input variable in the computation of PM model, one can assume that its determination was made with good precision, get by frequently check of psychrometry quality measurements throughout the experiment.

Maximum transpiration (T) occurs when there is no soil water deficit and may be considered equal to sap flow values integrated for 24 hours intervals (VALANCOGNE & NARS, 1993; TREJO-CHANDIA et al., 1997). Figure 4 presents correlation between T estimates and sap flow data (SF). Data of plant 2 (LA=13.9m^2) and 4 (LA=6.0m^2) show the high deviation related to SF. The model overestimated SF data in 56% for plant 2, while underestimated in about 30% for plant 4. T estimates for plants 1 and 3, with intermediate LA values, had a good agreement to SF with angular coefficient (b) close to unity. R^2 values varied from 0.41 to 0.57 and Test F indicated that all regressions were statistically significant at 1%. Linear coefficients of four equations are not statistically significant at 5%, therefore trend lines were forced to start at origin.

Table 2. Diurnal mean values of leaf conductance (gl), standard deviation (SD) and coefficient of variation (CV) for five days of measurements in a coffee plant.

Julian day	mean gl mm s^{-1}	SD mm s^{-1}	CV
254	1.36	0.75	65%
267	1.30	0.52	41%
289	0.92	0.78	90%
295	1.13	0.62	53%
297	0.90	0.79	94%

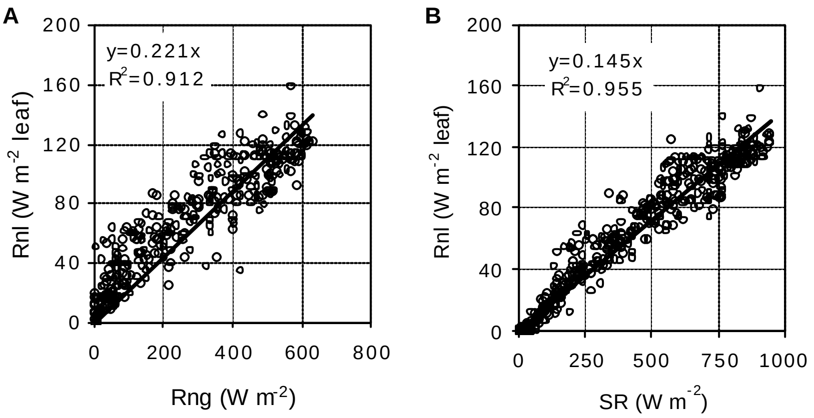

Figure 3. Relationship between radiant energy absorbed per leaf area unity (Rnl) and net radiation grass (A), and with incoming solar radiation (SR)(B). Data obtained at each 15 minutes.

to be valid for coffee plants cultivated in a high density system. Studying the extinction coefficient and energy absorbed in a plant in the same coffee plantation where this experiment was realized, MARIN et al. (2003) verified that coffee cultivated in high density population may present some limitation in energy absorption ability. This "self-shading" characteristic is pronounced in plants with high LA, reducing the amount of energy that reaches inside leaves and inferior layer of coffee canopy. Studying photosynthesis rates in whole coffee canopies MARUR & FARIA (2003), found that plants with low AF had the highest photosynthesis rates, which agree with data obtained here.

Because two plants with extreme LA values had presented discrepancies in relation to SF, Rnl was pointed out as the main reason for this, since this variable is the only one that does not consider any individual plant characteristics. Sampling all coffee plants together and establishing a unique relation for calculation of Rnl for all of them, one implicitly accept the assumption that LA has a direct linear relationship with radiant energy absorbed. However, it seems not

Thus, one may expect that LA and Rnl are related by an non-linear rather than a linear equation, which maximizes Rnl in plants with low LA and minimizes Rnl in those with high LA. Therefore the Rnl estimates for plants 2 and 4 with relations presented in Figure 3 would be respectively above and below of hypothetical real Rnl values for both plants. Figure 5 summarizes this hypothesis and the good agreement observed in plants 1 and 3 acts to confirm it since their LA were close to the mean LA of the four plants.

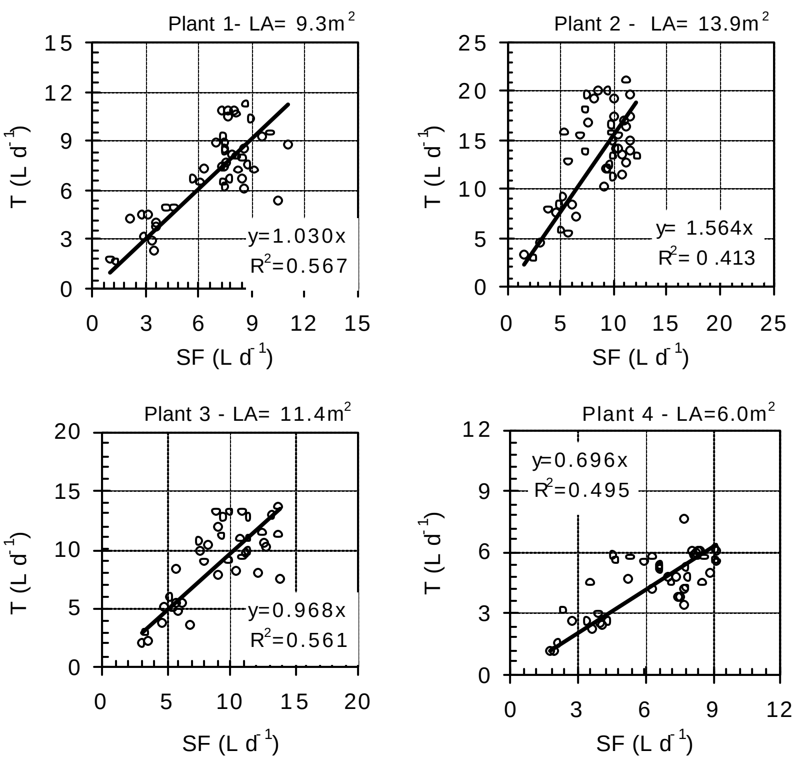

Figure 4 Relationships between maximum transpiration estimated by Penman-Monteith model (T) and sap flow(SF) for four coffee plants .

An way to evaluated these considerations is applying PM model for four plants together, simulating the transpiration of a big coffee plant with LA=40.6m^2 and comparing it with the sum of SF of four plants. Figure 6 shows this correlation using mean ra and rl values of four plants in PM model. The value of b close to unit indicates the good performance of PM model for coffee plants even though the low R^2, and main problem in estimates of individual plants was due to the form of measurement of Rnl.

Conclusions

- Penman-Monteith model can be used to estimate maximum transpiration of coffee plants, but

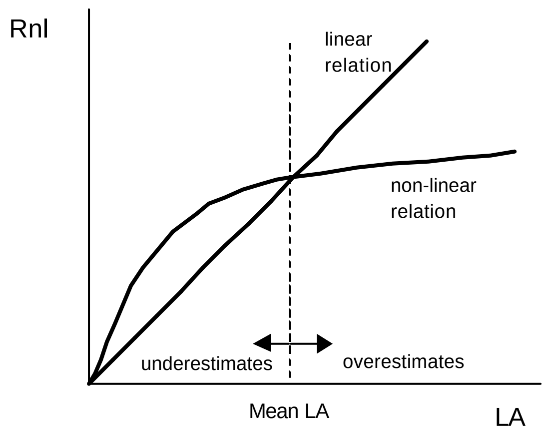

Figure 5. Hypothetical differences of linear and non-linear relation between radiant energy absorption (Rnl) and leaf area (LA) on the Penman-Monteith model performance to estimate maximum transpiration for coffee plants.

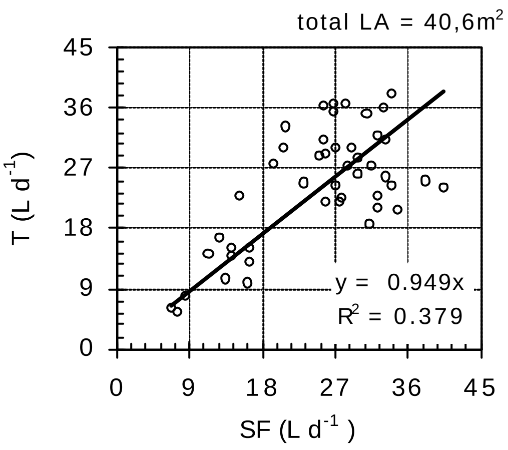

Figure 6. Relationship between estimated maximum transpiration (T) for a hypothetical coffee plant with 40.6 m^2 and the sum of sap flow (SF) of four coffee plants.

further studies about its input variables are still necessary.

- Uncertainties in evaluation of aerodynamic resistances estimates are mainly due to the difficult in attainment of reference values. Studies about absorbed net radiation must focus the development of more universal models, based on porosity, leaf density and others specific plant parameters. The discrepancies verified for plants with extreme leaf area value was caused by the system used to measure the absorbed radiant energy, which sampled four plants simultaneously.
- For coffee plants leaf area and absorbed radiant energy had a non-linear relationship.

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