

Leaf area and solar radiation interception by orange tree top

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Abstract

Leaf area changes affect solar radiation interception (K^*), interception efficiency (ϵ_{int}) and extinction coefficient (k) of an orange tree top (cv. Pêra-Rio). In order to measure radiation transmitted through the crown a mobile sensor was horizontally installed below the crown and 0.65 m from the trunk, moving around it at 3 rpm. The model used for k determination (Monsi & Saeki theory) was assessed with independent data to estimate K^* . With absence of leaves, it was detected an intense interference of trunk and branches on ϵ_{int} with a minimum value of 0.52. The results were also distinct in obtaining k , when the best fit was found with a quadratic rather than a linear equation, again influenced by woody structures. Simulation of K^* using extinction coefficient (k) was statistically classified as good.

Key words: *Citrus sinensis* L. Osbeck, leaf area index, interception efficiency, extinction coefficient.

1. INTRODUCTION

Transpiration and photosynthesis of a plant, its yield and production quality, and its microclimate characteristics, essentially depend on the absorbed solar radiation, conditioned by leaf area and its efficiency of interception of radiant energy.

The availability of solar radiation at the Earth's surface is primarily related to the variables associated with the Earth-Sun relationships, while the magnitude of this radiation interception by a tree, for example, further depends on architecture and the density of canopy foliage (associated with leaf area and porosity of the crown) as well as the optical properties of vegetation and the relationship between direct and diffuse radiation.

The transmitted fraction that reaches the surface below the canopy is crucial for the establishment of biotic factors, their characteristics and disturbances (Endler, 1993). However, few studies have focused on solar radiation regime of species whose foliage suffers from natural or anthropogenic disturbances, which promote sharp changes in the foliage density, leading even to the complete absence of leaves (Baldocchi et al., 1984; Federer, 1971; Wang & Baldocchi, 1989).

There are countless crops that have periods of absence or reduction of foliage due to natural dormancy, adverse environmental conditions, or even motivated by pruning

and harvesting. The presence of foliage gaps in the crown plays important role in radiation transmittance, producing qualitative and quantitative changes of radiant energy available for the strata below the canopy or at soil surface, enabling or enhancing the natural occurrence of plants in those strata and even causing temporal morpho-physiological changes (Buler & Mika, 2009; Cardoso et al., 2010; Machado et al., 2002; Pezzopane et al., 2002).

This study aimed to quantify the changes in the interception of solar radiation by orange tree canopy, cv. Pêra-Rio, caused by variation of leaf area, and to fit and validate a simulation model of solar radiation intercepted by the canopy.

2. MATERIAL AND METHODS

The study was conducted in Piracicaba, São Paulo State (22°42' S; 47°30' W; 546 m), in an orange grove (*Citrus sinensis* L. Osbeck) cv. Pêra-Rio. The soil of the area was classified as Red Nitosol. Data collection was carried out for 19 days between May 6th and June 24th, 2005. The spacing between trees was 8.0 m x 4.0 m and plant height was 3.5 m. Planting rows had the northwest-southeast orientation, with azimuth of 165°. With roughly spherical

geometry of the canopy and mean diameter of 3.3 m, the horizontal projection area of the canopy (PA) was 8.6 m².

To determine the leaf area (LA) of the orange tree, it was initially used a portable meter of leaf area index (LAI) (LAI-2000 Canopy Analyser, LI-COR). From the LAI x PA product, it was determined leaf area (LA) of the canopy.

From that determination, four manual defoliations were performed successively. In each defoliation, it was collected and counted all the leaves randomly taken from the canopy (NI), measuring the maximum length (L) and maximum width (W) of 100 leaves. Mean values L and W were adopted to calculate the total leaf area of the tree (Equation 1) using a correction factor 'f' equal to 0.7 (Coelho et al., 2005), allowing estimation of the initial value LA (without manual defoliation) and the determination of other post-defoliation values.

$$LA = \bar{L} \cdot \bar{W} \cdot f \cdot NI \quad (1)$$

With data of LA and PA, it was determined the initial and post-defoliation values of leaf area index (Equation 2):

$$LAI = \frac{LA}{PA} \quad (2)$$

From digital photos of the silhouette lateral foliage of the canopy, and using the software QUANT, it was determined the fractions of porosity or percentage of voids (p%), foliage (f%) and woody material (m%) of the canopy.

Data of global solar radiation 'Qg' (Kipp & Zonen pyranometer, CM-3) were collected in the weather station of the Department of Biosystems Engineering at ESALQ/USP, distant about 300 m from the experiment. To measure the fraction of Qg transmitted by the orange canopy ('τQg') a pyranometer LI-200 (LI-COR) was attached to a circular metal frame, component of a mobile system of measurement, rotating around the canopy, similar to that described by Angelocci et al. (2004) and McNaughton et al. (1992). By the movement of this system around the tree, the pyranometer turned horizontally around the trunk at a distance of 0.65 m at 3 rpm, performing a space-time sampling of solar radiation transmitted to below the canopy. Mean values of 15 minutes of Qg and τQg were stored by data loggers (CR1000 and CR23X, Campbell).

Only data collected between 10 and 14 hours were used, thereby preventing direct incidence of solar radiation on the transmissivity measuring sensor, without the interaction of the radiant energy with the foliage and woody structures of the canopy.

The solar radiation intercepted by the orange canopy (K*) was calculated from measurements of incident solar radiation (Qg) and the fraction transmitted (τQg) through the canopy (Equation 3):

$$K^* = Qg - \tau Qg \quad (3)$$

The solar radiation interception efficiency (ϵ_{int}) was determined from the ratio of the intercepted solar radiation (K*) and total incident (Qg) on the orange tree canopy (Equation 4):

$$\epsilon_{int} = \frac{K^*}{Qg} \quad (4)$$

From diurnal mean values (10 to 14 hours) of solar radiation interception efficiency (ϵ_{int}), the porosity of the canopy taken considering the silhouette area of the canopy (p%) and values of leaf area index (LAI), it was determined the normalized interception efficiency by using the fraction 'S' filled of the canopy silhouette (leaves + woody material) (Equation 5) and the canopy extinction coefficient (k), estimated from the Monsi & Saeki theory, on the basis of requirements of Beer's law, expressed by the Equation 6 (Hirose, 2005):

$$\epsilon_{int} / S = \frac{\epsilon_{int}}{\left(1 - \frac{p(\%)}{100}\right)} \quad (5)$$

$$\ln(1 - \epsilon_{int}) = -k \cdot LAI \quad (6)$$

With some modifications, Equation 6 was used to estimate the interception of solar radiation by orange tree canopy (K*_{est}). The model was tested with measurements taken at 15 minute intervals, and their values integrated for part of the daytime (10 to 14 hours). A set of independent data of K* measures, covering all LAIs (no LAI=0), was used to evaluate the model:

$$K^*_{est} = Qg \cdot (1 - e^{-k \cdot LAI}) \quad (7)$$

where: Qg is global solar radiation, k is extinction coefficient and LAI is the leaf area index.

For analysis of results, it was used the following statistical indicators: coefficient of determination (R²); correlation coefficient (r); agreement index (d) (Willmott et al., 1985) and coefficient of reliability or performance (c) (Camargo & Sentelhas, 1997). The values of 'c' were classified as optimal (OP) for values greater than 0.86; very good (VG.) between 0.76 and 0.85; good (G) between 0.66 and 0.75; regular (RG.) between 0.51 and 0.65; poor (PO.) between 0.41 and 0.50; and very poor (VP.) for values less than 0.4. The performance classification was based on the statistical indicator 'c', and other indicators served to support classification and discussion of results.

3. RESULTS AND DISCUSSION

From the leaf area (LA) of the orange tree top, of 37m², horizontally projected on the soil (PA), it was observed an initial leaf area index (LAI) of 4.33. With the removal of 26.2%, 51.03% and 67.6% LA, it was obtained LAIs of 3.20; 2.12 and 1.40. After final defoliation that eliminated completely the foliage (LAI=0), it was possible to separately quantify the interception of solar radiation by trunk and branches only.

During the days of measurement, between 10 and 14 hours, the global solar radiation (Q_g) showed considerable variations (Figure 1a). For the time of maximum radiation (12 hours), it was recorded values from 531.3 W m⁻² to 749.0 W m⁻², averaging 635.5 W m⁻² and

a standard deviation of 49.56 W m⁻². As the measurements extended over approximately 2 months, starting with a solar declination (δ) of 16.68° N and ending with δ of 23.40° N, the reduction in solar radiation coincided with the decrease of leaf area of the tree canopy (Figure 1b), but the period of measurements without foliage showed values higher than days with LAI = 1.40. Values measured of Q_g, when the LAI of orange tree was 1.4, were 20% lower than those measured with maximum LAI. Quantitative and qualitative variations affect the interception and utilization of solar radiation by vegetation, inevitably interfering with the results (Federer, 1971; Rowland & Moore, 1992).

The variation in interception efficiency (ε_{int}) dependent on the leaf area index of orange tree, including measures with LAI=0 (Figure 2a), enabled an exponential fit between

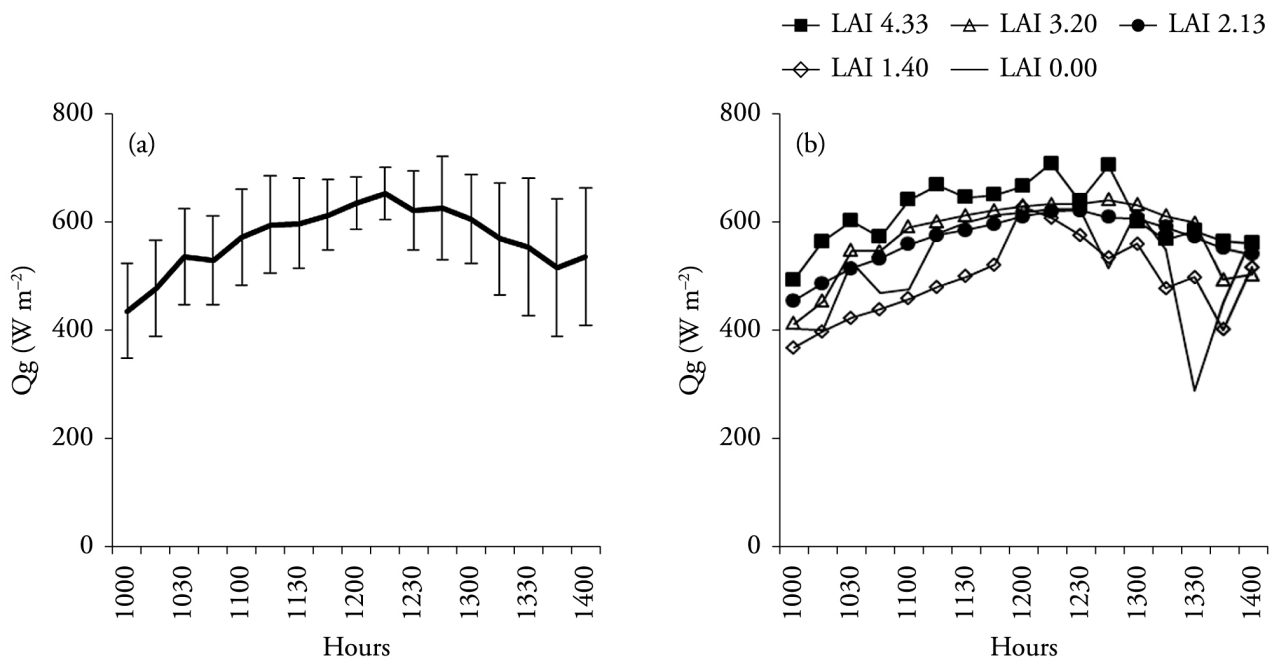


Figure 1. Mean variation and standard deviation bars of solar radiation (Q_g) in the period between 10 and 14 hours for all days of measurement (a) and mean values of Q_g for days with different LAIs (b).

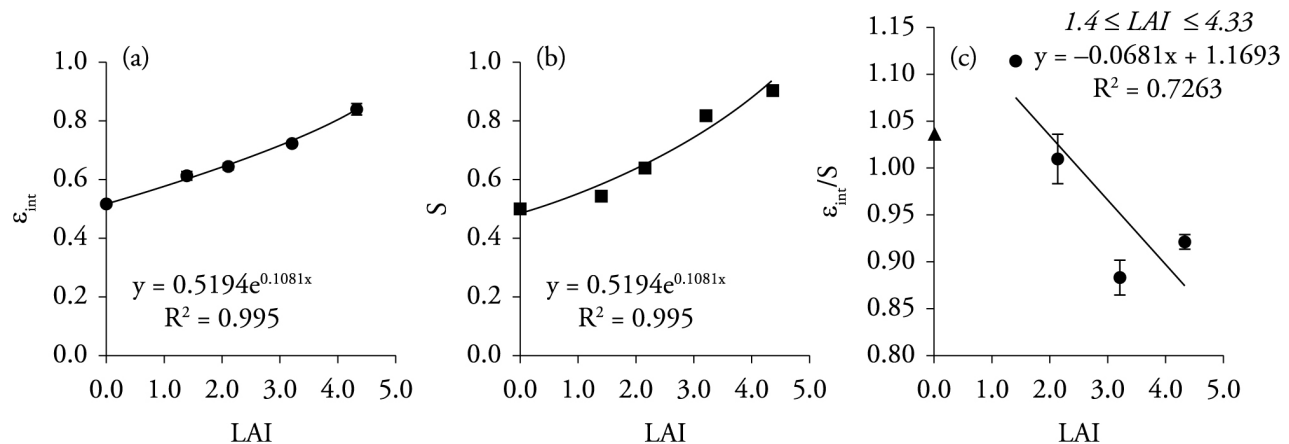


Figure 2. Interception efficiency (ε_{int}) of solar radiation (a), percentage of canopy silhouette filling ‘S’ (b) and ε_{int} normalized by S (‘ε_{int}/S’; (c)), as a function of LAI of an orange tree cv. Pêra-Rio. Bars indicate the standard deviation. Mean data of the period 10-14 hours.

variables, such as the statistical fit also achieved for annual cycle crops (Bergamaschi et al., 2010; Kunz et al., 2007; Lindquist et al., 2005; Müller & Bergamaschi, 2005; Radin et al., 2003). Moreover, canopy morphology originated a characteristic value of ϵ_{int} (Figure 2), distinct from that observed for annual crops, defining a high canopy interception efficiency even in the complete absence of foliage.

To normalize ϵ_{int} relative to S , we obtained an inverse correlation with LAI (Figure 2c). Increasing canopy porosity intensifies the transmissivity of solar radiation, increasing the multi-reflection and the interception of radiant energy by silhouette soil coverage unit. While ϵ_{int} was reduced from 0.83 to 0.52, due to total removal of the foliage (Figure 2a), the filling of the canopy had a greater reduction, from 0.912 to 0.502 (Figure 2b and Figure 3). In the absence of leaves, exposure of woody material therefore contributes to reduce the global canopy reflectivity (Liakatas et al., 2002), increasing ϵ_{int} (Figure 2c).

The interception model of solar radiation (Q_g) according to the foliage canopy (LAI) (Figure 2) resembles that obtained for an isolated palm tree (Awal et al., 2005). For canopies of deciduous species, in the complete absence of leaves, up to 50% of radiant energy incident on the top

can be intercepted (Federer, 1971; Liakatas et al., 2002; Zavitskovski, 1982), logically with significant variations depending on the vegetation characteristics, the direct/diffuse radiation relationship, the zenith angle and surface slope (Federer, 1971; Rowland & Moore, 1992).

This result confirms the difficulty of studying the distribution of incident solar radiation in canopies of trees or forests, given the roughness and inhomogeneity (wood/foliage ratio) of the canopy (Figure 3), so that, in most cases, these plant structures are simplistically considered continuous and homogeneous (Nerozzi et al 1997; Ross, 1981), disregarding, in fact, the total area of foliage and woody material, as well as its vertical distribution, the slope angle of these elements and their optical properties, which jointly control the radiant energy transfer in the canopy (Hutchison et al., 1986).

Changes in foliage and increased exposure of woody matter in tree canopy will always be determinant of transmittance (Figure 2) and radiation balance, even with qualitative interference of incident radiant energy in the lower strata of canopies, influencing the establishment and production of both natural surfaces (Floyd et al., 1978) and agroforestry systems (Caron et al., 2012).

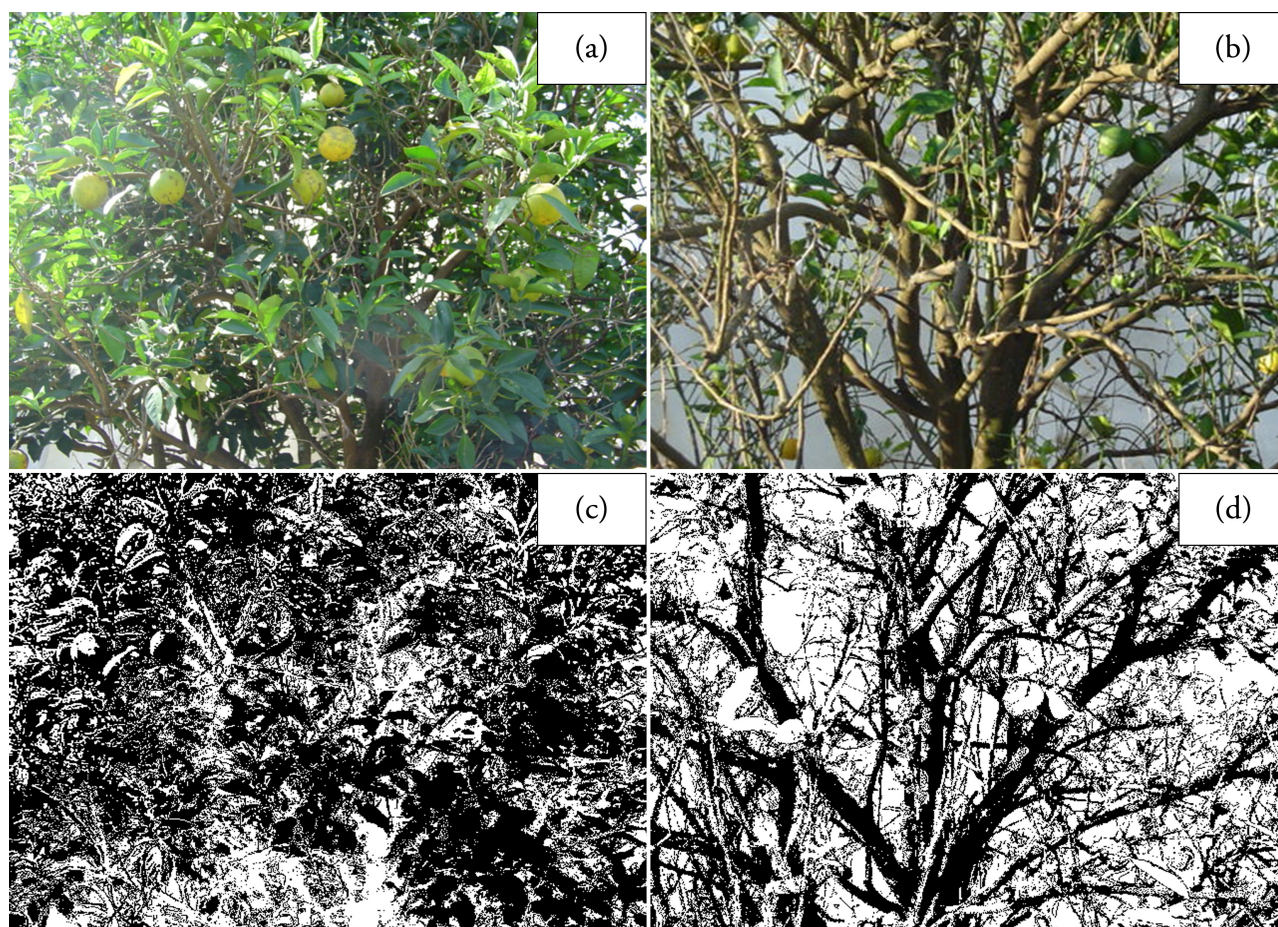


Figure 3. Side partial view of the top of an orange tree cv. Pêra-Rio, with LAI= 4.33 (a) and LAI = 1.4 (b) and their processed images, highlighting in black the flat area of the silhouette covered with foliage (c), for LAI = 4.33, and with woody material (d) for LAI = 1.4.

For annual crops, the extinction coefficient of global solar radiation or photosynthetically active fraction (PAR) is the angular parameter (α) of linear function $\ln(1-\epsilon_{int}) = -k \cdot LAI$ (Bergamaschi et al., 2010; Cardoso et al., 2010). However, for Pêra-Rio orange tree, the extinction coefficient (k), from the solar radiation interception efficiency (ϵ_{int}) and the LAI, exhibited a distinct result. From the ϵ_{int} recorded for LAI=0 (Figure 2) and hence a negative value of the term $\ln(1-\epsilon_{int})$ (Figure 4), the linear fit achieved between the variables generated an equation with distinct linear coefficient equal to -0.6298 (Figure 4a). The correlation between $\ln(1-\epsilon_{int})$ and LAI was even better fitted by a quadratic equation (Figure 4b) with R^2 very close to unity.

Estimates of solar radiation interception by orange tree canopy (K^*_{est}), using the extinction coefficient (k) obtained by linear (Figure 4a) and quadratic (Figure 4b) fit, were higher than data measured (K^*) for 15 minute intervals. Although the estimated results (K^*_{est}) were similar, with overestimates, the adoption of extinction coefficient k (Quadratic fit) resulted in a better fit of the model ($R^2 = 0.8573$) (Figure 5a). For 4 hour periods (10 to 14 hours), estimates (K^*_{est}) were once again higher than those values measured (K^*), but with better fit (R^2) (Figure 5b).

Estimated data, when compared with measurements, regardless of the adopted k (Figure 4), showed good correlation (r), but quantitatively closer to each other (d) when using

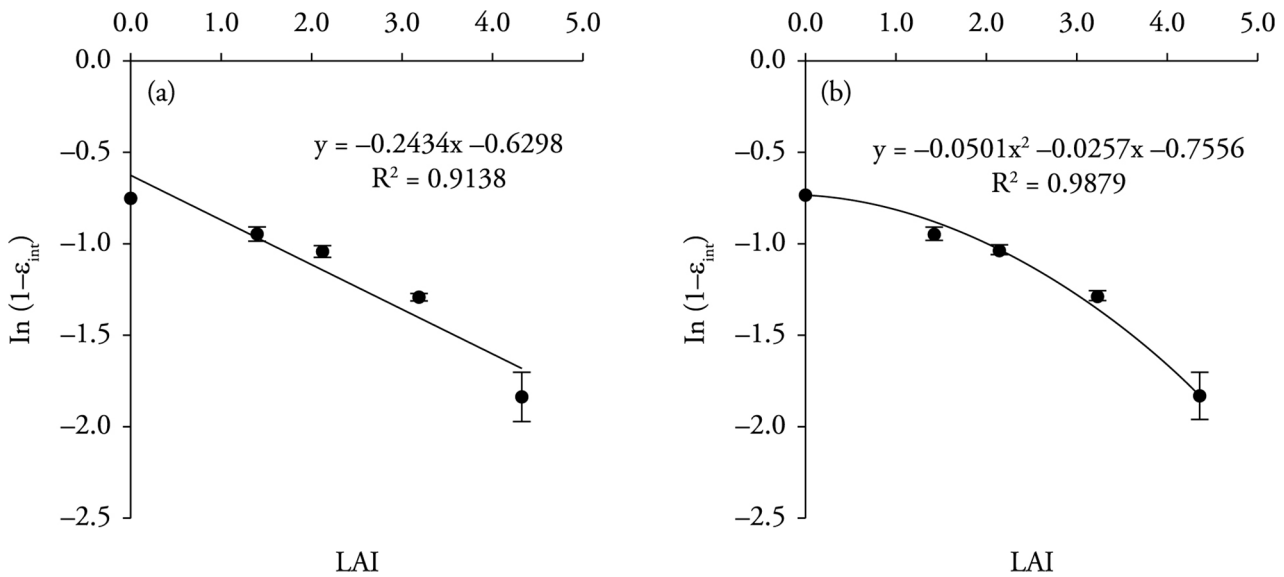


Figure 4. Extinction coefficient for solar radiation according to leaf area index (LAI) of an orange tree cv. Pêra-Rio, for linear (a) and quadratic (b) fit. Bars indicate the standard deviation. Mean data of the period 10-14 hours.

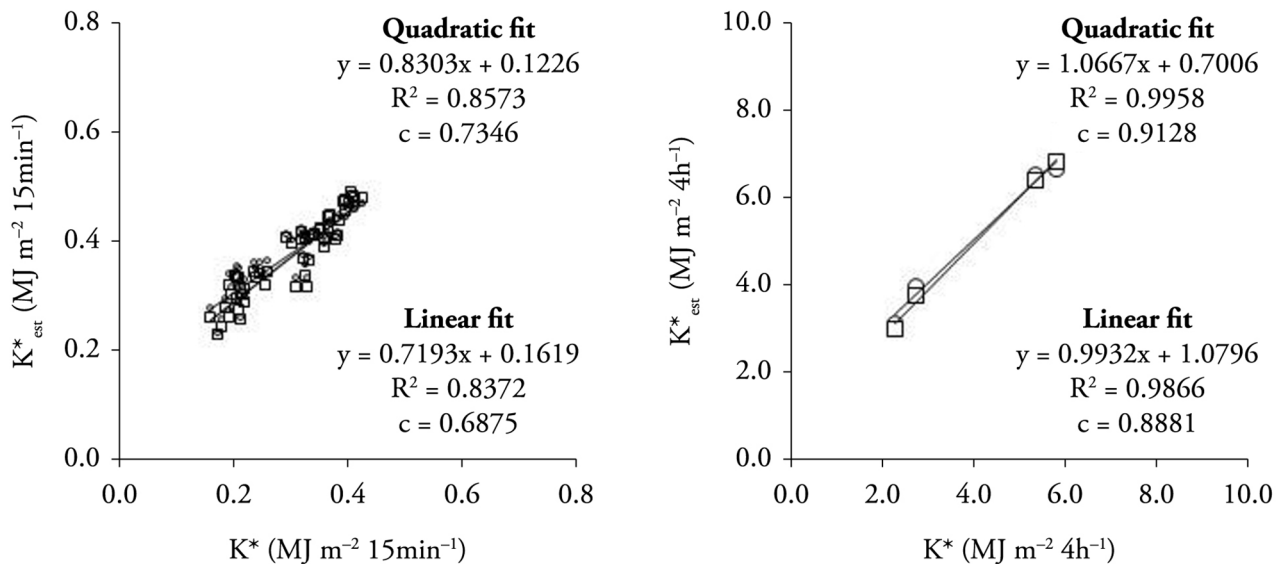


Figure 5. Correlations between integrated values at 15 min and 4 h of the estimated intercepted solar radiation (K^*_{est}) and measurement (K^*) of an orange tree top cv. Pêra-Rio with different values of LAI, from the fitted coefficients k .

the extinction coefficient obtained from the quadratic fit. In this sense, the use of this coefficient k (Figure 4b) to estimate K^* provided the best results, achieving 'optimal' classification according to the index c (Figure 5). The adoption of k (Linear fit) culminated in a lower performance, but still with values of ' c ' classified as 'good'. Satisfactory results of this estimate of K^* proposal for tree species were also obtained by Jackson & Palmer (1979) and Angelocci et al. (2008) in apple and in coffee.

4. CONCLUSION

The reduction in leaf area of the canopy, and consequent increase in porosity determined an exponential reduction of solar radiation interception efficiency.

Even in the absence of leaves, the branches allowed the canopy to maintain a minimum efficiency of interception of 0.52, compared to the maximum value of 0.83 for the highest leaf area index observed.

The model based on Beer's law was effective in simulating the interception of solar radiation by orange tree canopy between 10 and 14 hours, in the period from May to July.

There are differences in the extinction coefficient for tree and annual crops, explained by morphological differences and distribution of plants on the area.

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