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Radiation balance of an orange tree in orchard and its relation with global solar radiation and grass net radiation

Balanço de radiação de uma laranjeira em pomar e sua relação com radiação solar global e com saldo de radiação de gramado

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Abstract: Solar energy absorbed by plants is one the main factors determining photosynthetic and transpiration rates, conditioning the growth and development of crops. Particularly for the absorption of all-wave and photosynthetically active radiation by tree canopies, which is affected by the geometry and the leaf area density of the canopy, the "Whirligig" device originally described by McNaughton et al. (1992), has been shown to be a useful tool. This kind of device was used to measure the amount of all wave radiation absorbed by an orange tree, cv. Pêra do Rio, in an orchard in Piracicaba, São Paulo State, Brazil. Measurements were carried out from October to December 2004 and in May and June 2005. The net radiation absorbed by the tree (Rnl) was correlated with global solar radiation (Rg) and grass net radiation (Rng) measured in a weather station, for 15-min, hourly and daily periods. Regression equations include the effect of different leaf area densities, obtained by progressive tree defoliation, on the radiation balance. Good fittings between Rnl and Rg or Rng were obtained for all time scales. The same was observed for the relationships between Rnl per unit of area projected vertically on the ground by the tree canopy (Rnl/PA) and Rg or Rng. The results showed the possibility to use transfer functions to estimate tree net radiation from common measurements of Rg or Rng, but this functions should be used with caution, because they are only valid for conditions of leaf area range and canopy geometry similar to those observed in the study.

Keywords: net radiation, incoming solar radiation, leaf area, “Whirligig” device

Resumo: A energia radiante absorvida pelas plantas é um dos fatores determinantes da taxa fotossintética e da transpiração, condicionando o crescimento e o desenvolvimento vegetal. Em vista da sua importância e do pequeno número de estudos de medida e estimativa do saldo de radiação para espécies arbóreas, foram realizadas medidas do saldo de radiação de uma laranjeira (Rnl), cv. Pêra do Rio, com um sistema móvel de integração espaço-temporal para árvores “isoladas”. O estudo ocorreu entre outubro/04 e junho/05, sob diferentes condições de densidade de área foliar, impostas por desfolha da árvore. As medidas foram correlacionadas à irradiância solar global (Rg) e ao saldo de radiação de gramado (Rng), medidas em estação meteorológica. Foram obtidos bons ajustes entre os valores de Rnl e Rg, nas escalas de 15 minutos, horária e diária, verificando-se ainda bom ajuste entre as variáveis quando consideradas as diferentes áreas foliares (LA), na escala diária. Bom ajuste também foi obtido entre Rnl por unidade de área de projeção da copa no solo (Rng/PA) e Rng, na escala horária. Os resultados evidenciaram a possibilidade de se encontrar funções de transferência para estimativa do saldo de radiação da árvore a partir de medidas rotineiras de Rg e Rng, mas que são válidas somente para árvores com faixa de valores de área foliar e com geometria da copa semelhantes às do pomar estudado.

Palavras-chave: saldo de radiação, radiação solar, sistema móvel de medidas, área foliar

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Introduction

Radiation absorbed by the plants is the energy source for their physical, physiological and biochemical processes, determining dry mass accumulation and water loss, as well as many characteristics of their microclimates (STANHILL et al., 1965; CAMPBELL & NORMAN, 1998; MELLO-ABREU et al., 2002).

In orchards, the planting geometry determines if the trees act as “isolated” plants, when using large spacing, or if they form hedgerows, affecting the amount of all-wave radiation absorbed by them. This amount has been determined by direct measurements (THORPE et al., 1978; McNAUGHTON et al.,1992), or estimated by models (MELO-ABREU et al., 2002) or even by establishing relations between radiation balance of the tree and global solar radiation or turfgrass net radiation (ANGELOCCI et al., 2004), both variables measured in weather stations.

A large spacing between trees is used in orange orchards and the knowledge of radiant energy absorbed by each tree is of interest in studies of photosynthesis and transpiration modelling. Measurement of all-wave and photosynthetically active radiation (PAR) absorbed by a tree is not an easy task. McNAUGHTON et al. (1992) described a device (“Whirligig”), with eight net radiometers and eight quantum meters rotating around a tree, allowing space and time integration of the all-wave radiation and PAR absorbed by the canopy. Data obtained by the “Whirligig” device have been used for modelling transpiration, photosynthesis and light interception of fruit tree canopies (GREEN & McNAUGHTON, 1997; GREEN et al., 2003). GREEN et al. (2001, 2003) claim that the “Whirligig” provides a direct and continuous measure of light interception by individual trees at a fine resolution.

ANGELOCCI et al. (1999, 2001, 2004) used the “Whirligig” to measure net radiation of acid lime trees. They correlated the measured values of canopy radiation balance Rn, normalized to the projected area PA of the canopy on the ground (Rn/PA), with the global solar radiation (Rg) and grass net radiation (Rng), in daily, 15-min and 30-min periods.

Correlating all-wave radiation absorbed by leaf area unit (Rnl) of a walnut tree, with leaf area of 26.4 m^2, determined by GREEN (1993) in Palmerston North, New Zealand, and of an acid lime tree cv. Tahiti, with leaf area of 39.9 m^2, in Piracicaba, Brazil, to grass net radiation (Rng), PEREIRA et al. (2001) found a single relationship between the two variables for both trees. However, they were unable to fit the observed relationships to data of McNAUGHTON et al. (1992) for a *Robinia pseudoacacia* plant, indicating the difficulty to find an unique transfer function between Rnl and Rng.

Considering that transfer functions to estimate net radiation absorbed by the canopy of a tree are dependent on the type of canopy and leaf density, the present study aimed to determine the relationships between radiation balance of an orange tree in an orchard measured by the "Whirligig" technique and global solar radiation or turfgrass net radiation measured in a weather station in two seasons and evaluate the influence of tree leaf area on these relationships.

Material and Methods

The study was carried out on the experimental fields of the “Luiz de Queiroz” College of Agriculture, University of São Paulo, Piracicaba, State of São Paulo, Brazil (22°42' S; 47°30' W; 546 m amsl), in an orange orchard, cv. Pêra Rio, spaced 4.0 m x 8.0 m, from October to December 2004 (mid to late spring) and from May to June 2005 (mid to late autumn), with the “Whirligig” device installed around a tree (Figure 1).

In the first period, the tree leaf area (TLA) was determined with a LAI-2000 canopy analyzer (Li-Cor, Lincoln, NE, USA). In order to study the effect of TLA on the absorption of all-wave net radiation by the tree, the leaf area was reduced during May-June by removing sequentially part of the leaves in four steps, keeping TLA to other values than the original 37.0 m^2, viz., 27.3 m^2, 18.2 m^2, 12.0 m^2 and 0.0 m^2. During each defoliation procedure, the number (N) of excised leaves was counted and their mean length (L) and width (W) were estimated from a sub-sample. The total leaf area of the excised leaves, in each defoliation, was estimated by the equation 0.70.N.L.W (MARIN, 2000) and, at the end the values were summed up to give the maximum value of TLA of the mid-autumn, which was practically the same (37 m^2) of TLA of the period October-December measured with the LAI-2000.

The measurements with the “Whirligig” device were carried out using the procedures described by McNAUGHTON et al. (1992). Our rotational device was composed by a vertical frame, consisting of two parallel inner circles with internal diameter of 4.30 m, and a third outer circle (diameter: 4.36 m), where the radiometers were fixed. The frame was built with iron tubes (0,02 m diameter) and had an opening at its bottom to allow its installation around the trunk. It was mounted on a horizontal turntable, rotating at 3 rpm, powered by a 6.5 HP petrol engine. The torque was transmitted to the turntable by an iron chain coupled to a gearbox.

Eight net radiometers model Q*7 (Radiation and Energy Balance System, Seattle, USA), were fixed on the frame, in an equi-latitudinal disposition, with intervals of 22.5°. Due to the opening at the bottom of the vertical frame, the top and the lower sensors were fixed, respectively, at latitudes of +78.75° and -78.75° and the remaining ones at + 56.25°, +33.75°, +11.25°, -11.25°, -33.75°, -56.25°.

Based on this disposition of the sensors, the integration procedure to calculate the value of Rn took into account the weighting factors for each mounting position, as described by McNAUGHTON et al. (1992). As reported by these authors, the calibration factors of the net radiometers are little affected by the inclination of the plate of the instruments, so the factors for each sensor determined for the horizontal position were adopted. A datalogger model CR23-X (Campbell Inc., Logan, UT, USA), fixed on the vertical frame, recorded the radiometers signals every second, with mean values stored every 15-min periods.

Data of global solar radiation (Rg) and grass net radiation (Rng) were obtained in a weather station located about 800 m from the orange orchard, with a CM3 pyranometer and a NR Lite net radiometer (Kipp & Zonen, Delft, Netherlands), respectively.

Figure 1. View of the device rotating around an orange tree.

Results and Discussion

The best fit for the relation between Rnl and Rg or Rng, on a 15-min time scale, was obtained by a second order polynomial equation in both seasons, for TLA=37.0 m^2 (Figures 2a, 2b and 3a).

The pattern of the curves is similar to those observed for the same time scale for acid lime in the same experimental site by ANGELOCCI et al. (2004), who adjusted sigmoid curves to their data and also observed negative values of the tree radiation balance when low values of Rg occurred. Maximum integrated value of Rnl on 15-min time scale were about 8 MJ in the present work, against about 15 MJ for the experiment with acid lime, but it is necessary to take into account the differences of leaf area between the acid lime trees (with maximum TLA of 51 m^2) and the periods of measurements throughout the year.

On the 1-hr time-scale, data of Rnl expressed per unit area of the canopy projected vertically on the ground (PA), were related to Rg and Rng (Figure 2c). Contrary to the curvilinear relationship between Rnl and Rg observed for this time scale by ANGELOCCI et al. (2004) in acid lime tree, the relation for the orange tree was better fitted by a linear model. In average, the all-wave radiation absorbed by unit of PA was equivalent to the incoming radiation in a horizontal area of 0.91 m^2.

On the 15-min scale the relation between Rnl and Rg was also well fitted by second-order polynomial models, when the leaf area was reduced, with different values of the equation coefficients for each value of TLA (Figures 3 and 4).

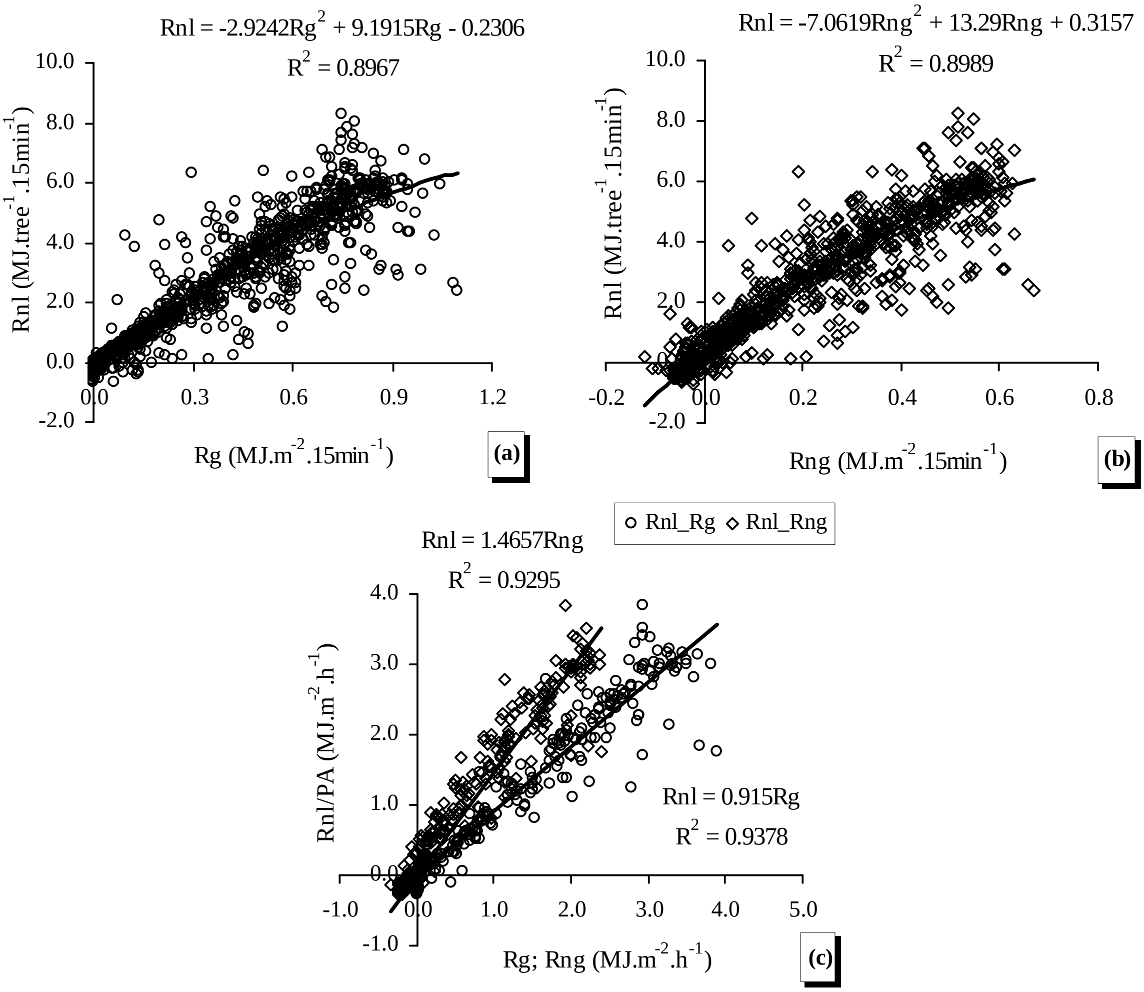

Figure 2. Relation between all-wave radiation absorbed by the orange tree (Rnl), and global solar radiation Rg (a) or net radiation over turfgrass (b) in 15-min periods, and between all-wave absorbed radiation by unit of projected area of the canopy on the ground (Rnl/PA), for leaf area of 37 m^2. October to December, 2004.

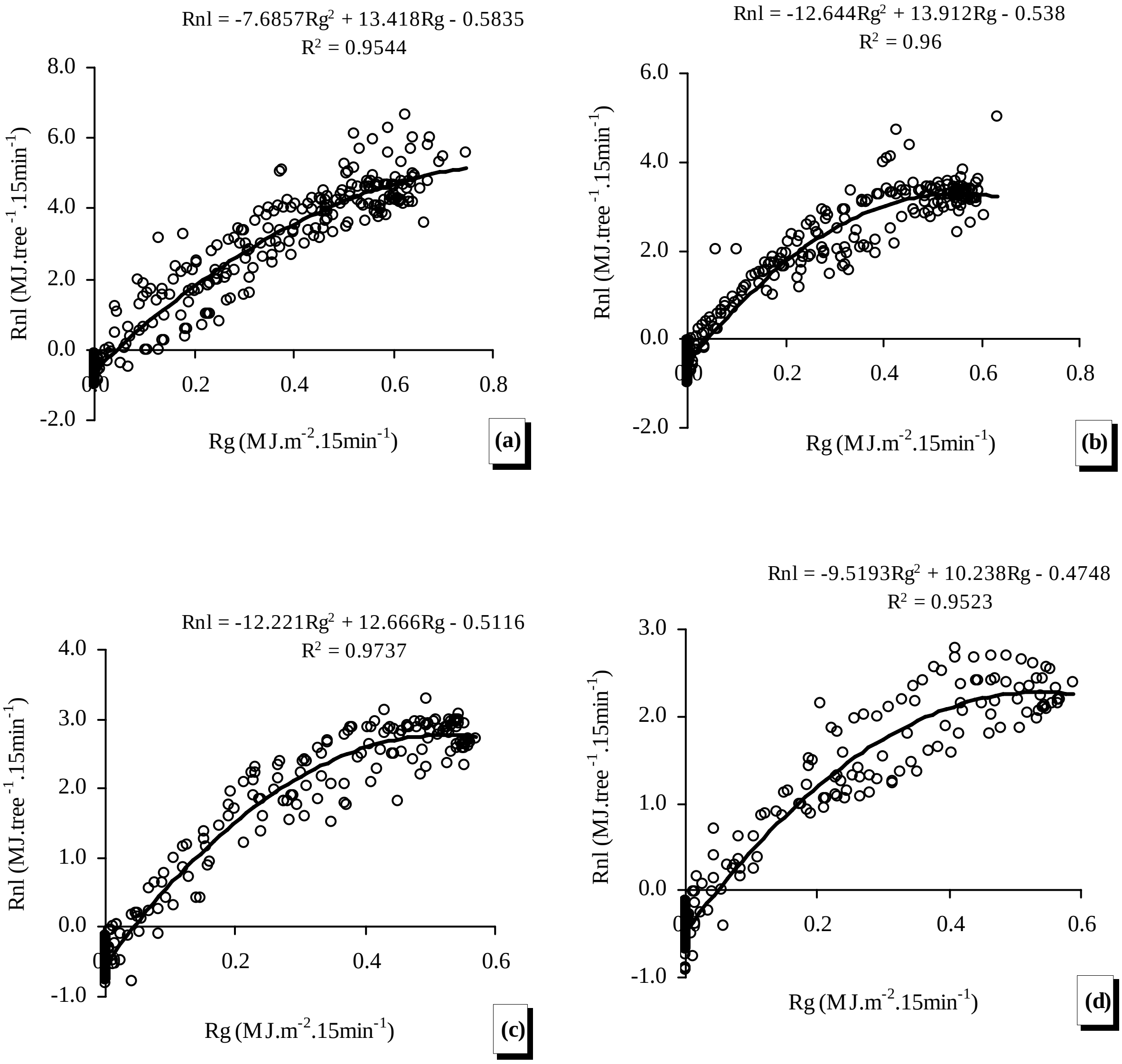

Figure 3. Relations between orange canopy net radiation (Rnl) and global solar radiation (Rg), for tree leaf area of 37.0 m^2 (a), 27.3 m^2 (b), 18.2 m^2 (c) e 12.0 m^2 (d), at 15-min time scale. Period: May-June 2005.

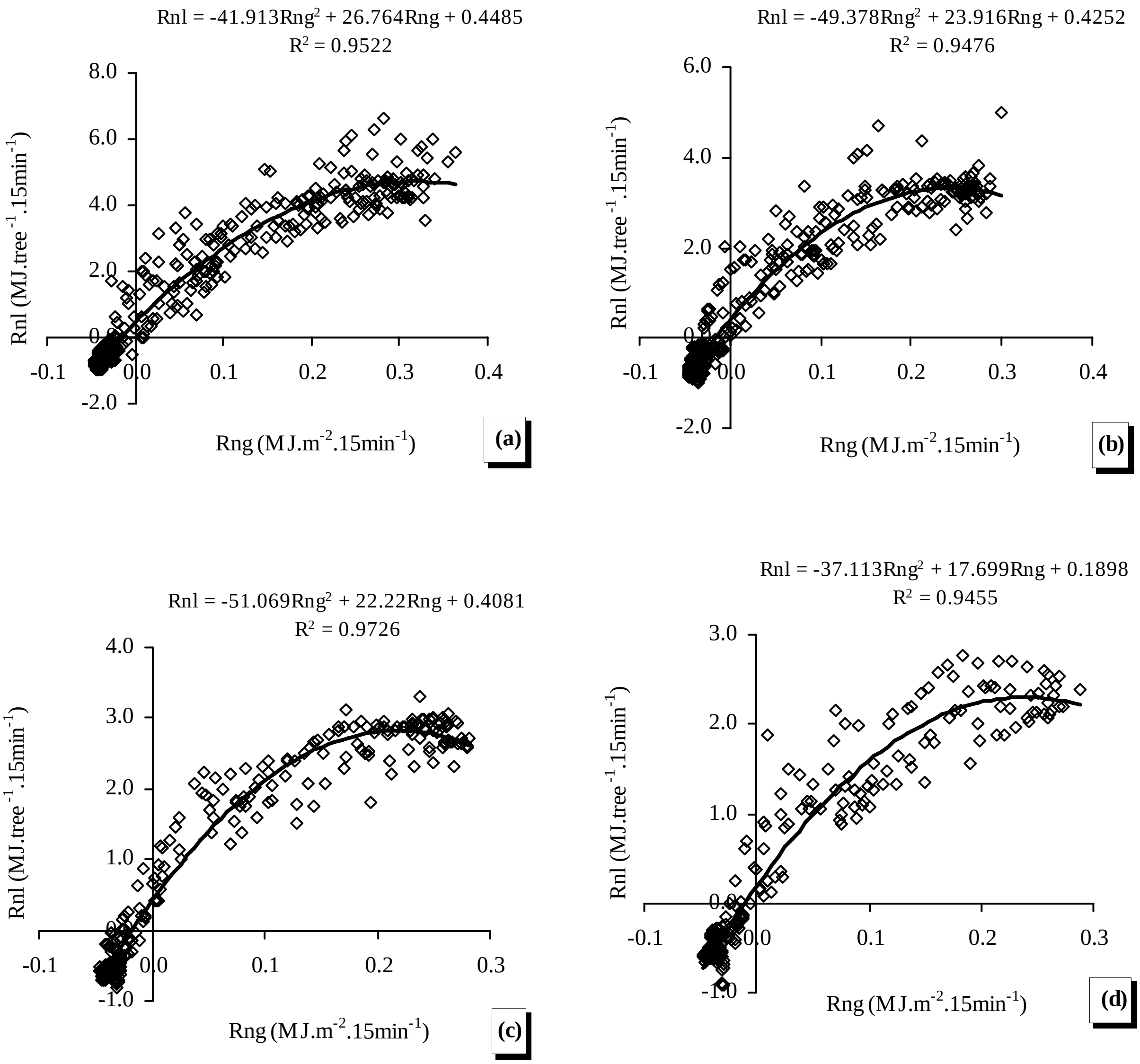

Figure 4. Relations between orange canopy net radiation (Rnl) and grass net radiation (Rng) for tree leaf areas of 37.0 m^2 (a), 27.3 m^2 (b), 18.2 m^2. (c) 12.0 m^2, (d), at 15-min time-scale. Period: May-June 2005.

While relatively stable relations between Rnl and Rg were observed in the two seasons, those between Rnl and grass net radiation (Rng) were affected by the season (Figures 2b e 4a, with TLA=37.0 m^2), with different values of the equation coefficients for October-December and May-June, as also observed by ANGELOCCI et al. (1999) in acid lime plants. Probably, this is a consequence of the change of the optical characteristics of the turfgrass throughout the year in the weather station, as observed by SENTELHAS and NASCIMENTO (2003), who found a seasonal change of the ratio Rg/Rng in the region.

The relations between tree net radiation per unit of ground area under the canopy (Rnl/PA) and global or turfgrass net radiation, on the hourly time-scale are presented in Figure 5. Both relationships were well fitted by linear equations for all different leaf areas, with reduction of their slopes according to decrease of leaf area. The slopes of the straight lines decreased proportionally lesser than the decrease of the tree leaf area.

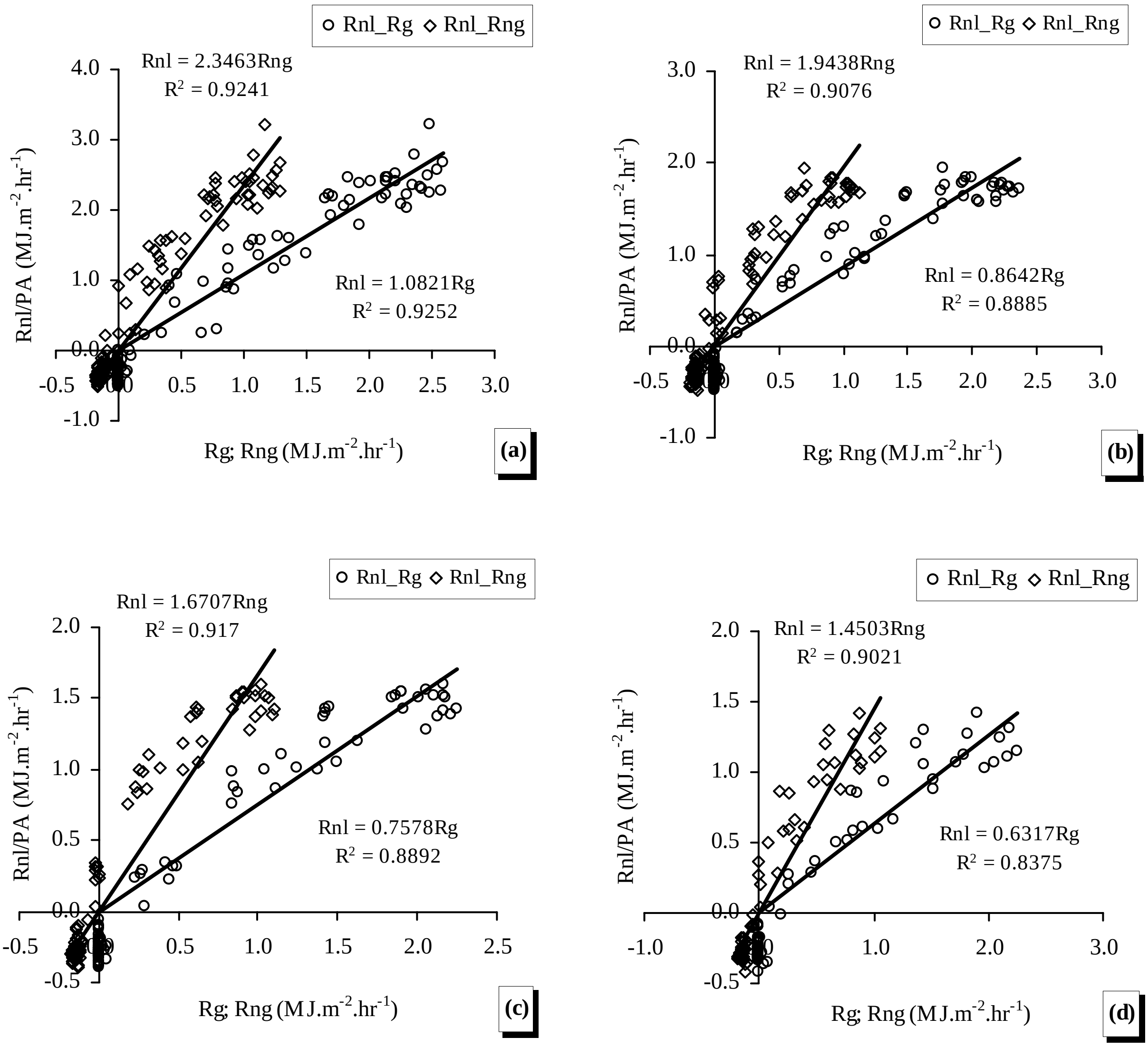

Figure 5. Relations between tree canopy net radiation per unit of ground area under the canopy (Rnl/PA) and global solar radiation (Rg) or grass net radiation (Rng), for leaf areas of 37.0 m^2 (a), 27.3 m^2 (b), 18.2 m^2 (c) and 12.0 m^2 (d), at hourly time-scale. Piracicaba, May-June2005.

A good correlation between Rnl/PA and Rg was also observed by ANGELOCCI et al. (2004) for two acid lime trees but, for the tree orange here studied, lower values of radiant energy absorption were observed when compared to those of the acid lime trees.

Linear regression equations also well fitted the relationship between (Rn/LA) or Rnl/PA and Rg in the daily period (Figure 6). The largest range of Rnl/LA (Figure 6a) was verified in 2004 for leaf area of 37.0 m^2, from 1.1 $MJ.m^{-2}.d^{-1}$ to 4.6 $MJ.m^{-2}.d^{-1}$. In the measurements in 2005 a lower range of values, from 2.10 $MJ.m^{-2}.d^{-1}$ to 3.39 $MJ.m^{-2}.d^{-1}$, was observed. ANGELOCCI et al. (2004), working with two acid lime trees in the same place, with leaf area of 51.2 m^2 and 39.9 m^2, found Rnl/LA ranging from 2.0 $MJ.m^{-2}.d^{-1}$ to 6.0 $MJ.m^{-2}.d^{-1}$.

The relations between the same variables (Rnl/LA and Rnl/PA) and Rng are presented in Figure 7. A larger determination coefficient was obtained for the relationship between Rnl/PA and Rng, than that obtained between Rnl/PA and Rg.

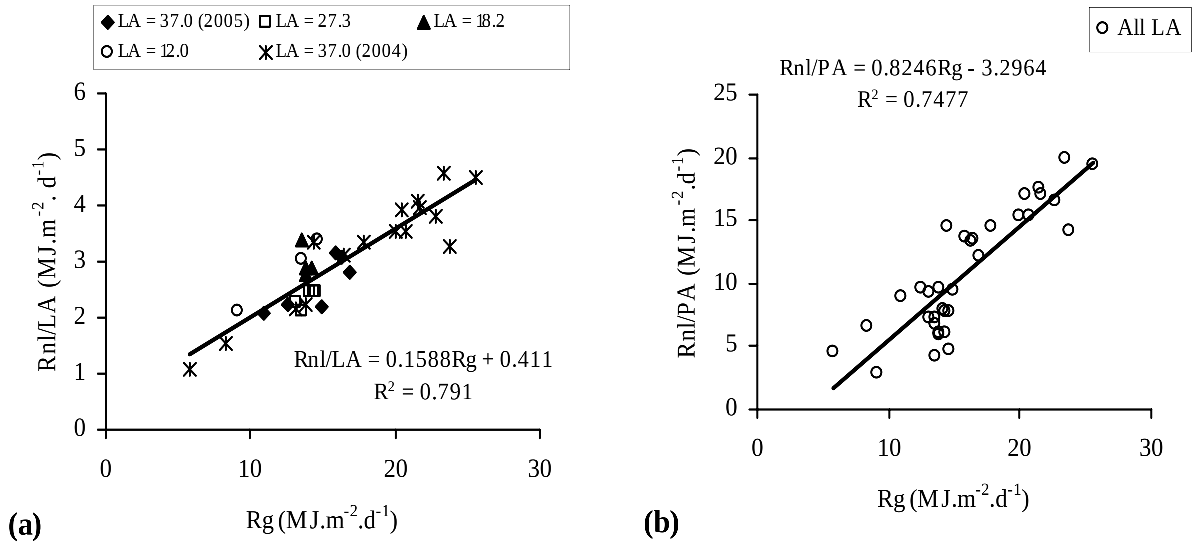

Figure 6. Relations between daily values of orange canopy net radiation by leaf area unit (Rnl/LA) and global solar radiation (Rg), with data points being showed separately for each leaf area and the two years (a), and with pooled data between tree net radiation per area unit canopy projected on the soil (Rnl/PA) and global solar radiation (Rg) (b).

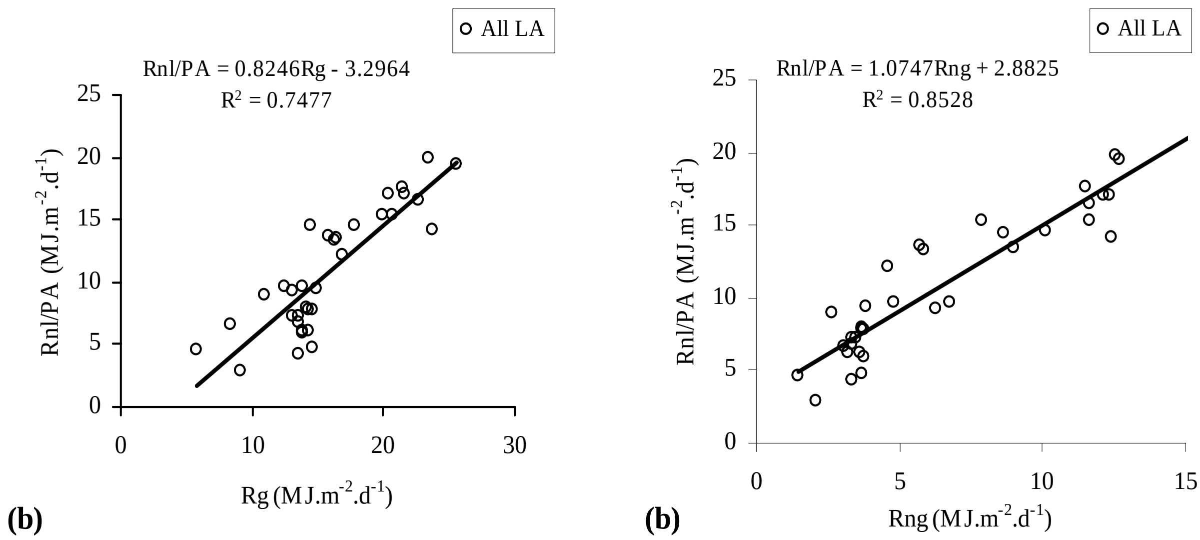

Figure 7. Relations between daily values of orange canopy net radiation per leaf area (Rnl/LA) and grass net radiation (Rng) for all leaf areas (LA) (a), and between orange canopy net radiation by area unit projected by the canopy on the ground (Rnl/AP) and grass net radiation (Rng) for all leaf areas (b).

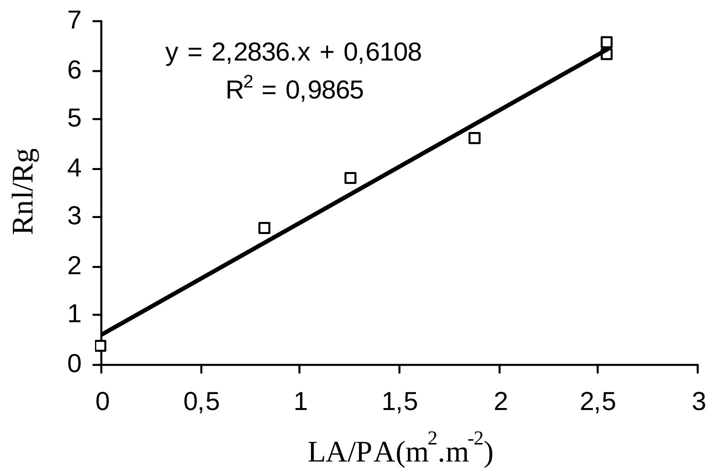

Figure 8. Relation between the mean values of Rnl/Rg and the leaf area normalized to the projected area of tree canopy on the ground (LA/PA).

The general effect of the leaf area on the radiation absorption is presented in Figure 8, where the mean values of the ratio Rnl/Rg were correlated with the leaf area per unit of ground area under the canopy (LA/PA). Data were well fitted by a linear equation. Starting from Rn/Rg equal to 0.61 for null leaf area (representing the absorption by the trunk and branches), this ratio increased proportionally to the increase of LA/PA, one unit increase of LA/PA representing 14.5 m^2 of leaf area. The linear relation observed shows that the relative effect of the trunk and the branches on the absorption of the incoming solar radiation is different for each leaf area, being one of the causes of the non-proportional decrease of the slopes of the relation with the decrease of the leaf area (see Figure 4).

Conclusions

The observed relations show that it is possible to find transfer functions for estimating all-wave absorbed radiation by orange trees, from measurements of global solar radiation or turfgrass net radiation and tree leaf area. However, caution must be taken to extrapolate the here obtained transfer functions for conditions of leaf area and canopy geometry different from those observed in this study.

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