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Measuring and modelling the radiation balance of an orange tree

Felipe Gustavo Pilau[1(*)] and Luiz Roberto Angelocci[1]

[1]Universidade de São Paulo - Escola Superior de Agricultura "Luiz de Queiroz". Av. Pádua Dias, 11, Caixa Postal 9, CEP 13418-900 Piracicaba, SP, Brazil.
E-mails: fgpilau@usp.br and lrangelo@usp.br
[(*)]Corresponding author.

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ABSTRACT

The crop radiation balance is related to plant transpiration and photosynthesis, being important in practical applications and theoretical studies envolving these two processes. For sparse and in hedgerows-forming crops, it is interesting to quantify the all-wave radiation absorbed by the canopy of single plants. In practice, direct measurement of radiant energy absorbed by a single plant is not an easy procedure requiring the positioning of several sensors incompassing the crown, whose measurements using the weight sum of radiation recorded by each sensor. Models to assess radiation balance of trees are the alternatives. Despite its simplifications, the model simulated reasonably well the all-wave net radiation of a citrus tree, tested for differente leaf area conditions on 15min-time (Willmott index of agreement, *D* from 0.95 to 0.97; RMSE from 0.33 to 0.77 MJ tree^{-1} 15 min^{-1} and BIAS from 0.09 to -0.41 MJ tree^{-1} 15min^{-1}). On a day-time the performance of the model kept reasonably well (D = 0.95; RMSE = 13.91 MJ tree^{-1} 15 min^{-1} and BIAS = -0.03 MJ tree^{-1} 15 min^{-1}).

Introduction

Tree canopy radiation balance is a driving variable for plant transpiration, photosynthesis or growth analysis, and irrigation management, for example, but net radiation absorbed by leaves of single trees has been measured in only a few cases (Thorpe, 1978; McNaughton et al., 1992; Green, 1993).

Perennial crops show a range of different planting configuration (e.g. "isolated" trees in large spacing or hedgerows) and canopy architecture. These features and size of trees usually make it difficult to measure the amount of radiation absorbed by the crown. One of the first specific methods (Landsberg et al., 1975; Thorpe, 1978) consisted of arranging radiometers around the tree crown such as a notional volume of measurement through which total radiation absorbed can be assessed by integration of the net inward radiation flux passing by each net radiometer.

An adaptation of this technique was provided by McNaughton et al. (1992), who used an apparatus named 'Whirligig' by them, which set sensors moving around a tree establishing a spherical geometry of measurement, improving spatio-temporal crown sampling. This procedure has been used in several isolated trees (Green, 1993;

Green et al., 1995, 2001; Green and McNaughton, 1997; Angelocci et al., 2004).

A method combining geometrical caracters (Landsberg et al., 1975; Thorpe, 1978) and spatio-temporal crown sampling idea (McNaughton et al., 1992) is described by a set of radiometers around the crown moving horizontally along a stretch of hedgerow, creating a notional cylindrical of measurements, scanning several plants (Marin, 2003; Angelocci et al., 2008).

As alternative to labored measurements, Charles--Edwards and Thornley (1973) proposed one of the first models for 'isolated'plants. The model considered uniform leaves distributed in an elliptical crown volume, intercepting radiation according to the Beer´s law. More elaborately, Röhrig et al. (1999) proposed a three-dimensional approach for it, assuming the crown volume subdivided in cubical units with variable leaf area filling.

At the same way, the radiation interception by a uniform canopy where leaves are randomly distributed in a given solid geometric form was presented by Green et al. (2003). The theorethical basis of the model followed Norman (1979), Norman & Welles (1983) and Wang & Jarvis (1990) models, considering absorption of direct and diffuse radiation energy in photosynthetic (400-700 nm) and near infra-red (700-3000 nm) wavelength bands. The results showed excellent fitting between estimated and measured "Whirligig" data.

The few works exploring the canopy radiation balance for descontinuous canopies or isolated trees leave room for further research dealing with physical-mathematical based models for tree all-wave net radiation estimation. This paper aims to propose and evaluate a model for a single orange tree canopy inside an orchard, validating its estimations with radiation balance measured throught the technique proposed by McNaughton et al. (1992).

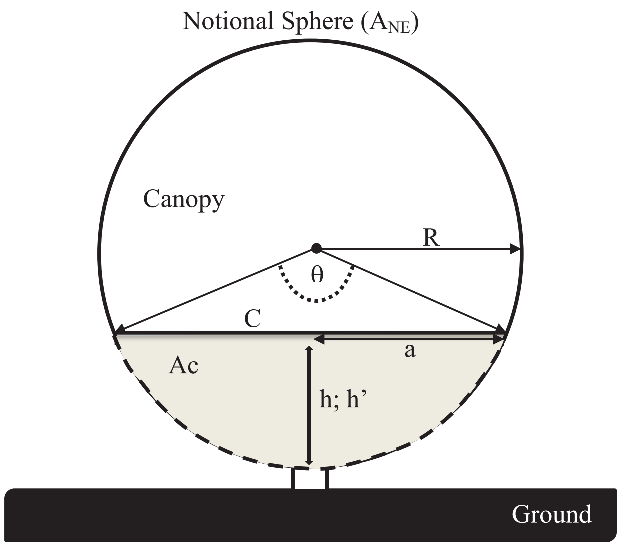
Material and methods

Local and biometric measurements

The all-wave radiation balance measurements (NRmes.) (Figure 1) were carried out in the central planting row of a citrus orchard, cv. Pêra-Rio, in Piracicaba, São Paulo state, Brazil (22.71´S, 47.62´W, 546 m). There were 15 days of measurements performed between day of year 126 to 174, 2005. The chosen tree was 4.0 m apart in rows with 8.0m between each row (standard orange planting). The planting rows were aligned northwest-southeast. Considering a spherical geometry to describe the citrus tree canopy (Figure 2), an average radius (R) 1.65 m was defined by vertical and horizontal measuments. In the bottom part of the crown, the absence of foliage shapes a cap of 1.3 m height (h).

Figure 1. Overall view of all-wave net radiation measurement done with 'Whirligig', atound an orange tree cv. Pêra-Rio. Piracicaba, São Paulo state, Brazil, 2005.

Figure 2. Geometric concept of the model for an orange tree Canopy (upper) and an empty cap (Ac) (bottom) integrating the notional sphere (A_{NE}). Pêra-Rio. Piracicaba, São Paulo state, Brazil, 2005.



The leaf area (LA) was first measured with a portable leaf area meter (LAI-2000). According to this LA reference, four manual defoliations were done later, decreasing about 25%, 50%, 70% and 100% of LA. All detached leaves (ln) were counted. Length (L) and width (W) of 100 leaves were measured, considering the average values $\overline{L}$ and $\overline{W}$ as representative of all the leaves. Tree leaf area was assessed by:

$$LA = LA_i - \bar{L}\,\overline{W} \ln f$$

where LAi is the leaf area before each defoliation and f is a specicific correction factor of form, 0.70 (Marin, 2000).

At the first day of measurement and after each defoliation the crown porosity (p) was accessed. The citrus tree was photographed at different cardinal positions, using a large white cloth extended behind the tree. Through digital images and software (Vale et al., 2001), p values were calculated. All-wave radiation balance measure with complete absence of leaves (total removal of foliage) was also performed, already reported by Pilau & Angelocci (2015).

Radiometric measurements

Global solar radiation (QRg) was measured at the weather station (-22°42'S, -47°38'W, 546 m) 900 m far from the orange orchard. Diffuse solar radiation (QRd) was measured with a piranometer under a shadow-ring device (Oliveira et al., 2002). The diffuse radiation data were adjusted due to the view area of sky obstructed by the metallic shadow-ring. Direct solar radiation (QRo) was accessed by the difference between QRg and QRd.

The reflection coefficient or albedo was measured with a pyranometer inversely positioned on the canopy, fixed approximately 1.5m internally at the upper part of the vertical circular frame of the 'Whirligig'.

All-wave net radiation measurement

Tree canopy all-wave radiation balance was measured with a device named as Whirligig (Figure 1), such as the one developed by McNaughton et al. (1992), with just a few structure details (Pilau, 2005). Basically, it was composed by a rotating circular frame of 4.3 m diameter, with eight net radiometers (REBS model 7) mounted on it at equi-latitudinal intervals (22.50). The rotation of the frame (3 rpm) around the tree generates a notional measurement sphere, used to integrate the net radiation in space and time. The procedures for the placement of the net radiometers computation method of measuring are detailed in McNaughton et al. (1992). The frame was fixed on a turntable powered by a 6.5 HP gasoline engine. The central pole of the frame used by McNaughton et al. (1992) was removed, because they have introduced a problem during insallation, as cited by these authors. A gearbox was used for speed reduction and the torque was provided by a transmission chain. The measures of every sensor were registered by a datalogger (Campbell Scientif Inc, CR23X) moving together the turntable and programmed to record every 10 s and store averages of 15 min.

Theoretical description of the model

The model is based on a notional sphere (ANE) of radius R interacting with long (L*) and short (K*) wave radiation. The crown volume filled by foliage and branches is effectively the upper part (Canopy) while in the bottom an empty cap (Ac) of height (h; h') shape the whole notional sphere (Figure 1).

According to zenith angle (Z), half of notional sphere (lateral surface area) intercepts direct (QRo) and the diffuse (QRd) solar radiation fractions together. The opposite face only the diffuse one (QRd). At the same time, according to solar movement (Z) a fraction of the cap (Ac') that makes up notional sphere (ANE) changes according to h size variation (h') (Figure 2). Therefore, the lateral area of ANE intercepting QRo (AQRo) is given by:

$$A_{NE} = 4\pi R^4 \tag{1}$$

$$Ac = 2\pi R h \tag{2}$$

$$h' = h - \{r - [\cos(90 - Z) r]\} \tag{3}$$

$$Ac' = 2\pi R (h - h') \tag{4}$$

$$A_{QRo} = \frac{4\pi R^2}{2} - \frac{Ac - Ac'}{2} \tag{5}$$

To set the lateral area which intercepts diffuse radiation (AQRd) the model considered the difference between the whole lateral area of ANE (Eq. 1) and Ac (Eq. 2), adding a circular base (Cb) area of radius (a) (Fig. 2)

$$a = \sqrt{R^2 - (R - h)^2} \tag{6}$$

$$Cb = \pi a^2 \tag{7}$$

$$A_{QRd} = A_{NE} - Ac + Cb \tag{8}$$

The model: (i) treats as negligible the energy stored in plant, (ii) foliage is randomly distributed in the canopy, and (iii) energy not intercepted by a canopy and hence reaching the ground is given using Beer's law. Although Beer's law is usually applied to uniform canopies and not individual trees, it is known that this proposition applying Beer's law to the vegetated fraction of the surface although a simplification of the real processes can be used without introducing a significant error (Domigo et al., 2000). Therefore, to define the leaf area index (LAI), the flat area

(FA) perpendicular to the zenith angle (Z), corrected by canopy porosity (p), is given by:

$$\theta = \left[2\,\mathrm{acos}\left(\frac{\mathrm{R - h'}}{\mathrm{R}} \right) \right] \tag{9}$$

$$\mathrm{A_{SC}} = \left[\frac{\mathrm{R}^2}{2} \left(\theta' - \mathrm{sen}\,\theta' \right) \right] \tag{10}$$

$$\mathrm{FA} = \pi\,\mathrm{R}^2 - \mathrm{Asc} \tag{11}$$

$$\mathrm{LAI} = \frac{\mathrm{LA}}{\mathrm{FA\,(1\text{-}p)}} \tag{12}$$

where θ is the angle of the circular segment of rope (C) (Figure 2) changeable according to the height h' (Eq.3), represented by θ' which defines the size of the semi-circular area (ASC).

Thus, considering the geometry of the crown, its temporal exposure to solar radiation, porosity or foliage gaps (p) and the coefficient of reflectivity (α), short-wave radiation balance submodel (K*) is described as followed:

$$K^* = \{[\,\mathrm{Q_{R_o}}(1\text{-}p)(1\text{-}\alpha)\,(1\text{-}e^{-k\mathrm{LAI}})\,\mathrm{A_{QRo}}] + [\mathrm{Q_{R_d}}\,(1\text{-}p)(1\text{-}\alpha).(1-e^{-k\mathrm{LAI}^*})\mathrm{A_{QRd}}\,]\} \tag{13}$$

where k is the coefficient of extinction described by Pilau and Angelocci (2015).

Due to the multidirectional nature of diffuse radiation (QRd), LAI* is defined by the ratio between leaf area (FA) and the crown projection area on the ground (PA) corrected by canopy porosity (p).

$$\mathrm{LAI}^* = \frac{\mathrm{LA}}{\mathrm{PA\,(1\text{-}p)}} \tag{14}$$

A model that takes into account the average air temperature (K) and partial vapor pressure (KPa), following the proposed by Brunt (1944) and Allen et al. (1998) was fitted using an independent set of long-wave radiation balance (L*) data.

$$\frac{\mathrm{L}^*}{\sigma T_{air}^4} = \mathrm{a} + \mathrm{b}\sqrt{\mathrm{ea}} \tag{15}$$

σ is the Stefan-Boltzmann constant; T^{air} is the air temperature (K); a = -0.23988, b = 0.125175 and ea is the vapor pressure (KPa)

Thus, considering the lateral area of the notional sphere (ANE) excluding the area of the cap (Ac), and adding the basal area of the crown (Cb), the following submodel is proposed to simulate the long-wave radiation balance (L*):

$$\mathrm{L}^* = \{[(-0.23988 + 0.125172\sqrt{\mathrm{ea}})(\sigma \mathrm{T_{air}^4})][A_{\mathrm{NE}} - \mathrm{Ac} + \mathrm{Cb}]\} \tag{16}$$

The performance of the model was evaluated based on the following statistical parameters: correlation coefficient (r), concordance index (Wilmott et al., 1985), root mean square error (RMSE) and BIAS index.

Results and discussion

The first measurements of all-wave radiation balance (NRmes.) were done with 37.0 m^2 of leaf area. At this time, the canopy porosity was 8.9%. After, defoliations sequence leaded to three more leaf areas, 27.3 m^2, 18.2 m^2 and 12.0 m^2, and respective porosities of 18%, 36% and 45%. Albedo (α) was typically larger at dawn and dusk, with maximum values around 0.38 reaching a minimum value at solar noon, the pattern of variation commonly observed for many land cover plants (Monteith & Szeicz, 1961; Baten & Kon, 1997; Alados et al., 2003; López-Olivari et al., 2015). The mean α was 0.18 with 37.0 m^2 and 27.3 m^2 of leaf area, keeping amost constant (0.17) after defoliation (18.2 m^2 and 12.0 m^2).

Measurements (NRmes.) were done between May and June, while natural decreasing of global solar radiation (QRg). It averaged maximum values of 0.64 MJ m^{-2} $15min^{-1}$ (706.7 W m^{-2}) for the highest leaf area (37.0m2) to 0.56 MJ m^{-2} $15min^{-1}$ (617.8 W m^{-2}) corresponding to minimum leaf area (12.0 m^2) (Figure 2). With low incoming solar radiation and leaf area (higher canopy porosity), all-wave radiation balance also showed to be decreasing (Figure 3). NRmes. reached 5.54 MJ $tree^{-1}$ $15min^{-1}$ and 2.58 MJ $tree^{-1}$ $15min^{-1}$, respectively, for the highest and lowest value of LA (Figure 3). At night the long-wave radiation balance (L*) was, for the previously mentioned LA, -0.82 MJ $tree^{-1}$ $15min^{-1}$ at -0.75 MJ $tree^{-1}$ $15min^{-1}$, reflecting QRg and diurnal NRmes. decreases, but also usual air temperature decline along experimental time (data not shown). These data (Figure 3) show similarities to those for citrus and even coffee trees (Simon & Angelocci, 2014), whose measurements followed Landsberg et al. (1975) and Thorpe (1978) proposal.

The measuring system (Figure1) all o wed detailed analysis about canopy foliage and incoming solar radiation relation and its long-wave radiation balance (Landsberg et al.1975; Thorpe, 1978; McNaguhton et al., 2002), exhibiting contrast results from those measured for homogeneous or sparse/arboreal canopies (Carrasco & Ortega-Farías, 2008) just by the simple setting of a net-radiometer over the plants (Figure 3). The measured data show, due to crown geometry, it's greater ability to intercep incoming solar radiation at higher zenith angle times (Green , 1993) (Figure 3). During the middle part of the day, when LA was 27.3 m^2, about 4.5 MJ tree^{-1} 15min^{-1} of energy was absorbed by the tree, equating to an average flux density about 162 W m^{-2} leaf area, being almost the same reported by Green (1993) for a 10 years old walnut with 26.4 m^2 of LA (160 W m^{-2} LA), also measuring with a Whirligig device.

Mean data of NRmes. for 24h-time was 99.15 MJ tree-^{1} d^{-1} (LA 37.0m2) with an exponential decay to 68.54 MJ tree^{-1} d^{-1}, 44.98 MJ tree^{-1} d^{-1} and 36.14 MJ tree^{-1} d^{-1} as LA decreasing, agreeing with the range of NRmes. data also reported by Green (1993) and Green et al. (1995). Limited data to the photoperiod-time ranging from 135.9 MJ tree^{-1} (37.0 m^2) to 66.35 MJ tree^{-1} (12.0 m^2) outlining the exponential NRmes. decrease due to canopy defoliation, while at night-time (Figure 3) mean NRmes. was -38.78 MJ tree^{-1} (all leaf areas) with a standard deviation of ±5.18 MJ tree^{-1}, without clear relation with leaf area.

The results of quarter-hourly radiation balance modeled showed good agreement between K* and NRmes. through photoperiod, showing the geometric model assumptions well simulated the three-dimensional canopy efficiency in intercepting solar radiation, especially at low solar elevation times (high zenithal angle) (Figure 4). At the same time-scale, maximum values of K* were 7.25 MJ tree^{-1} 15min^{-1} related to maximum (37.0 m^2) to 3.32 MJ tree^{-1} 15min^{-1} with minimum LA (12.0 m^2). For daily time-scale mean values of K* ranged from 172.40 MJ tree^{-1} d^{-1} to 82.63 MJ tree^{-1} d^{-1}, respectively from highest to lowest LA. These results, compared to NRmes. for positive incoming solar radiaion time were 25 to 33% higher.

Regarding to L*, as expected, daily negative mean va-

Figure 3. Daytime mean course of all-wave net radiation measurements ($NR_{mes.}$) and global solar radiation (Q_{Rg}) for each leaf area (LA), on an orange tree cv. Pêra-Rio. Bars mean the standard deviation. Pêra-Rio. Piracicaba, São Paulo state, Brazil, 2005.

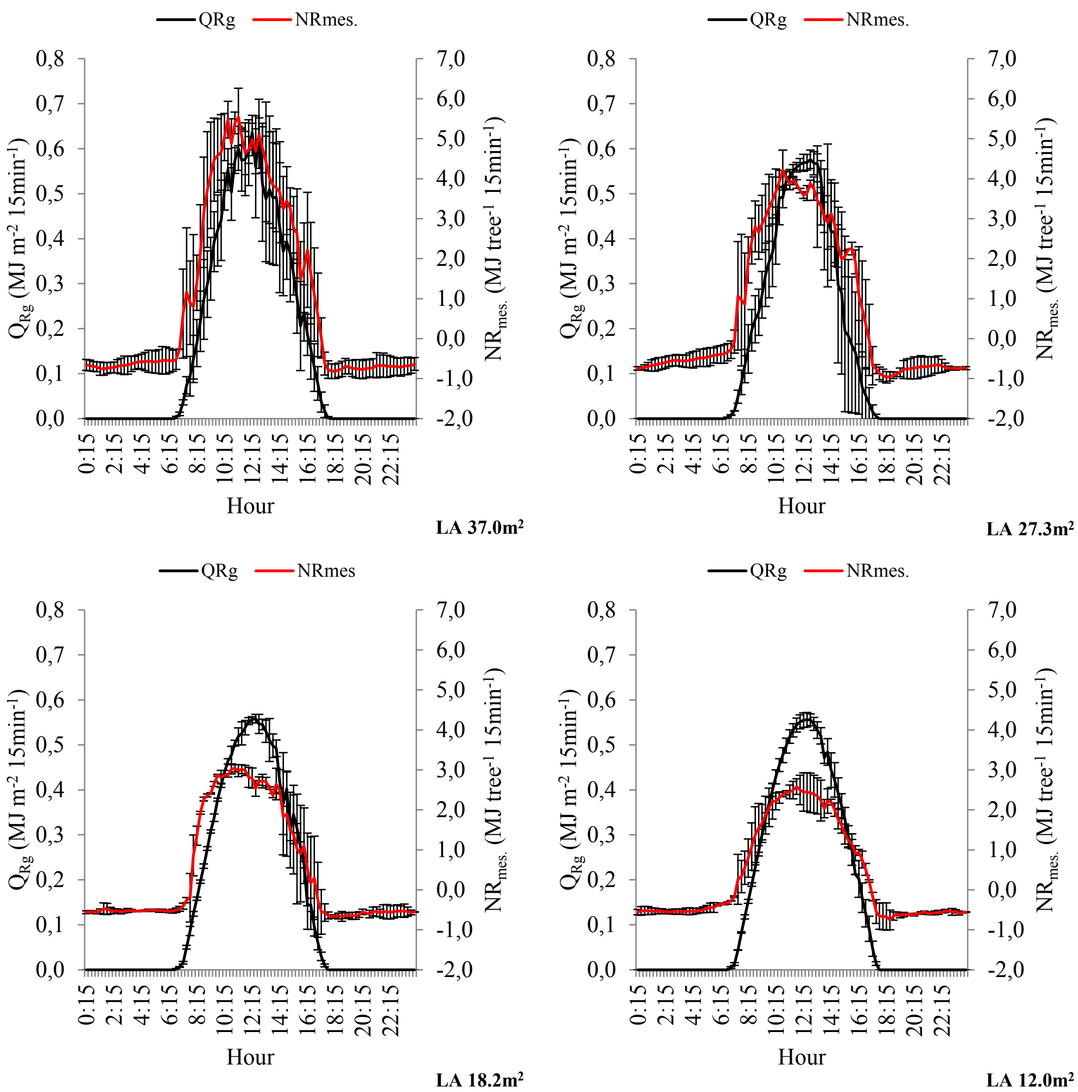
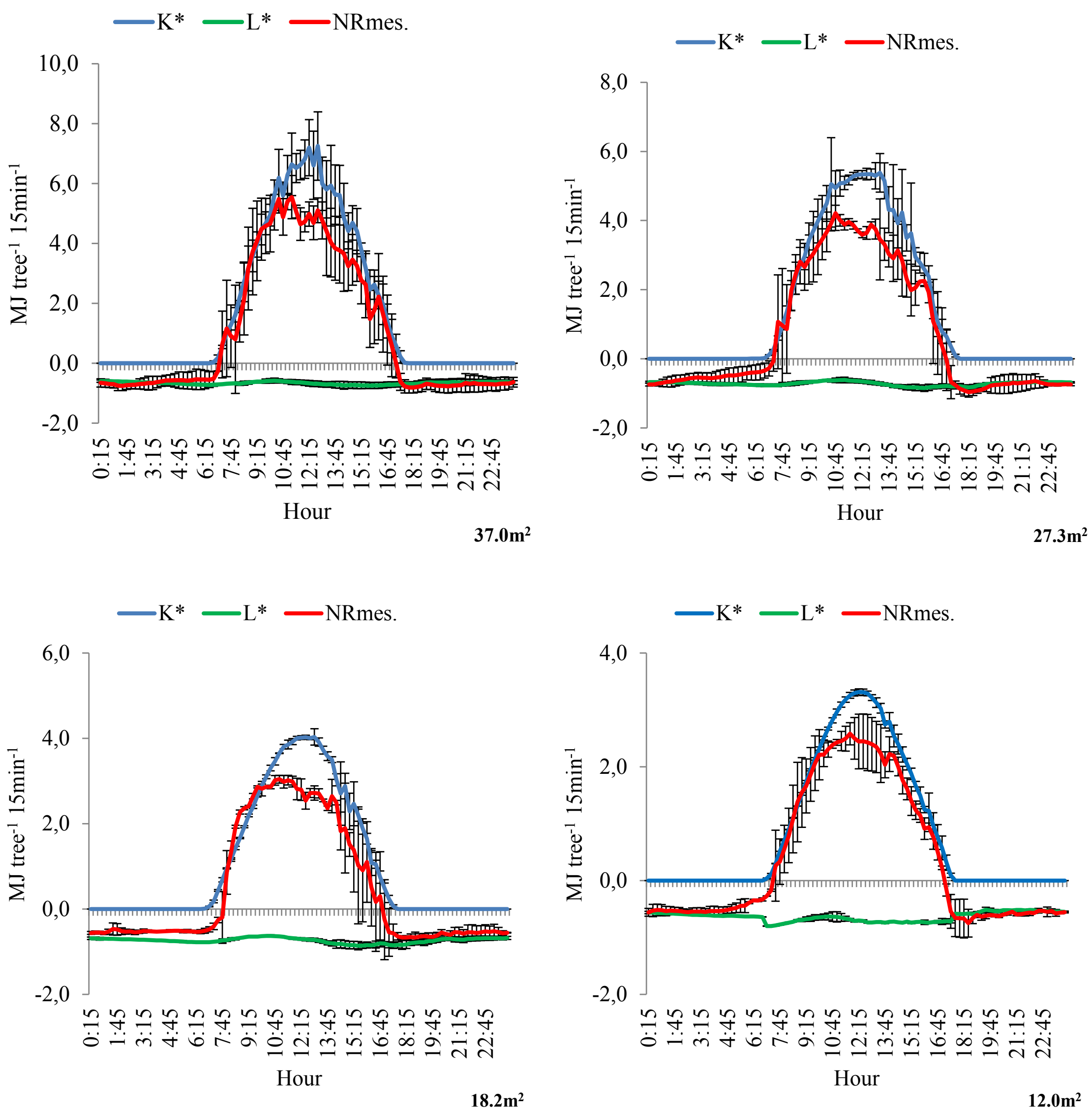


Figure 4. Daytime course of the amount of short (K*) and long (L*) wave radiation balance modeled and all-wave radiation balance measured with "Whirligig" (NR_{mes}), on an orange tree cv. Pêra-Rio. Pêra-Rio. Piracicaba, São Paulo state, Brazil, 2005.



lues kept between -0.64 MJ tree^{-1} 15min^{-1} to -0.74 MJ tree^{-1} 15min^{-1}. Minimum L* for all leaf areas were from -0.75 to -0.86 MJ tree^{-1} 15min^{-1}. For photoperiod-time L* ranged from -26.46 MJ tree^{-1} to -27.87 MJ tree^{-1} considering all modeled data. Thus, the ratio L*/NRmes. were from 20.5% for highest (37.0 m^2) to 40.5% for lowest (12.0 m^2) leaf area. Data of L* at 15min or photoperiod-scale match the range data reported by Stanhill et al. (1966) for an orange orchard as well as the ratio L*/NRmes.

Individual analyzes by leaf area (Table 1), once again, support the ability of the proposed model at 15-min frequency to simulate the effect of leaf area on all-wave radiation balance. According to statistical indexs there were high correlation (r) and agreement (d) between modeled and all-wave net radiation measured (Table 1). Besides that, RMSE results showed good accuracy of the proposed model. BIAS index showed the model overestimated the measurements for larger values of leaf area (37.0 m^2 and 27.3 m^2) and underestimated the situation of lower ones.

The results at daytime-scale (Figure 5) kept high correlation (r) and agreement (d) between modeled and all-wave net radiation data, but again express the model is less suitable for smaller leaf areas due to RMSE and BIAS results.

The agreement between predicted values by the proposed model and tree net radiation (Figures 4 and 5) by the Whirligig technique is lower than that observed by Green et al. (2003) for apple trees. For 15-min period, r ranged from 0.95 to 0.97 with a degree of scattering of data (Table 2) which could be caused as much as by model errors as by the Whirligig measurements as pointed out by McNaughton et al. (1992). It is difficult to devise an absolute

Table 1. Statistical analisys of the model performance, according to correlation coefficient (r), concordance index (d), root mean square error (RMSE) and BIAS index, for different leaf areas (LA) of an orange tree cv. Pêra-Rio. Pêra-Rio. Piracicaba, São Paulo state, Brazil, 2005.

LA (m^2)	r	D	RMSE (MJ tree^{-1} 15min^{-1})	BIAS (MJ tree^{-1} 15min^{-1})
37.0m2	0.962	0.980	0.68	0.09
27.3m2	0.946	0.960	0.77	0.10
18.2m2	0.956	0.975	0.46	-0.32
12.0m2	0.970	0.980	0.33	-0.41

test of accuracy for the data obained by this device, but it seems to be possible to make reliable and accurate measurements with it.

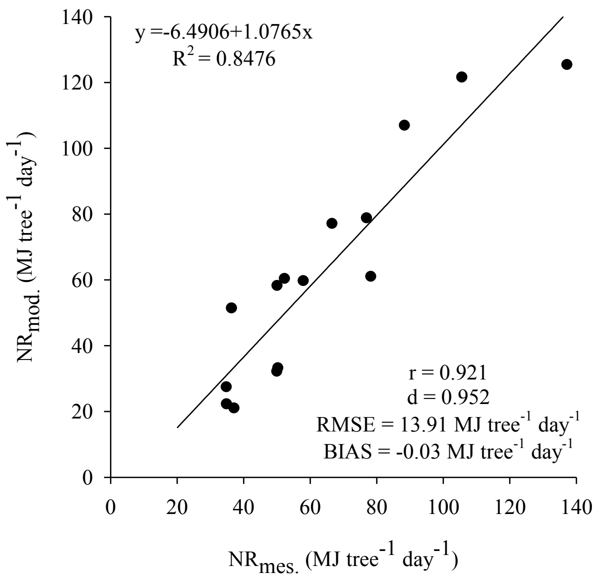
Altough some attempts have been made in using models to simulate light interception by single trees (Charles--Edwards & Thornley, 1973; Warren Wilson, 1981), their results were not confronted with measures that consider crown geometry and interaction with the radiation, as proposed by the Whirligig. They have rather been more common the use of three or two-dimensional light array models with validation by measurements performed by radiation sensors located close to the soil or in the lower parts of the canopy, as in the papers by Wang & Jarvis (1990) and De Castro & Fetcher (1998) for forests, and by Annandale et al. (2004) and Carrasco & Ortega-Farías (2008) for fruit orhards. The exception founded is the paper of Green et al. (2003), who founded a very good agreement between predicted and measured values of the two variables (PPF and Qn) for apple trees, with values of r^2=0.95 and slope of the linear regressions between simulated and observed values within 5% of the 1:1 line.

Even though the simplification used and applied in the proposed model, it reached a good performance level for different crown leaf areas. Also, it matters to highlight the requirement further studies in other conditions of planting designs and species.

Conclusion

The model seems to be potentially useful to assess tree canopy net radiation in orchards, replacing difficult and costly measurement with multiple sensors positioned around the crown. Better results were obtained for daytime integrated values. Low errors were found for different leaf area orange canopies. Due to its simplicity and relative ease found meteorological and biometric input parameters, the model can be easily implemented.

Figure 5. Predicted ($NR_{mod.}$) and measured ($NR_{mes.}$) values of the total amount of all-wave radiation absorbed by "Pera" orange tree for all leaf areas at daytime scale, on orange tree cv. Pêra-Rio. Pêra-Rio. Piracicaba, São Paulo state, Brazil, 2005.



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Medida e estimativa do balanço de radiação da copa de uma laranjeira

Felipe Gustavo Pilau[1(*)] e Luiz Roberto Angelocci[1]

[1]Universidade de São Paulo - Escola Superior de Agricultura “Luiz de Queiroz”. Av. Pádua Dias, 11, Caixa Postal 9, CEP 13418-900 Piracicaba, SP.
E-mails: fgpilau@usp.br e lrangelo@usp.br
[(*)]Autor para correspondência.

INFORMAÇÕES

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RESUMO

A medida da energia radiante absorvida pela copa de uma única planta em um cultivo arbóreo não é um procedimento simples. Para tal exigem-se equipamentos móveis e o posicionamento de vários sensores no entorno da copa, cada um amostrando uma fração da área total, formando uma esfera nocional de medição. Ao invés desses procedimentos, peculiares da pesquisa, o balanço de radiação de plantas em cultivos comerciais pode ser quantificado através de modelos. Nesse trabalho, além da medida direta do saldo de radiação, apresenta-se uma modelagem dos balanços de ondas curtas e longas da copa de uma laranjeira, cv. Pêra-Rio. Dados medidos do balanço de radiação, utilizados para ponderar o desempenho do modelo, consideraram a alteração da área foliar da copa conseguida por desfolhas manuais sucessivas. Apesar da simplicidade o modelo simulou satisfatoriamente o balanço de radiação da copa da laranjeira na escala temporal de 15 minutos frente a todos os valores de área foliar da copa (índice de concordância de Willmott (D) de 0,95 a 0,97; RMSE de 0,33 a 0,77 MJ arvore^{-1} 15 min^{-1} e BIAS de 0,09 a -0,41 MJ arvore^{-1} 15min^{-1}). Na escala diária o modelo manteve o bom desempenho, com índice de concordância de Willmott (D) de 0,95; RMSE de 13,91 MJ árvore^{-1} 15 min^{-1} e BIAS de -0,03 MJ árvore^{-1} 15 min^{-1}.

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