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Estimating single tree net radiation using grass net radiation and tree leaf area

Estimativa do saldo de radiação de árvore isolada usando saldo de radiação de gramado e área foliar da árvore

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Abstract *- Two sets of data of daily total net radiation absorbed by single trees (Qn, MJ d^{-1}) were analyzed, being: one, for an isolated walnut tree with 26.4m^2 of leaf area, in Palmerston North, New Zealand; and another, for an acid lime citrus tree of about 40m^2 of leaf area, grown in a small orchard in Piracicaba, SP, Brazil. In both trees Qn values was determined by a revolving device supporting net radiometers (8 for the walnut and 6 for the citrus) placed in a equilatitudinal distribution. Daily total "measured" Qn was determined by adding the contribution of each sensor weighted with its fractional sampled area. Correlating Qn with the standard weather station grass net radiation (Rng, MJ m^{-2} d^{-1}) it was found that such relationship was a function of the tree leaf area (TLA), that is, Qn was directly proportional to TLA within the range of leaf area used. Making Qn* = Qn / TLA (MJ m^{-2} of leaf area d^{-1}) it correlated well with Rng, giving the unique relationship Qn* = 0.32 (± 0.02) Rng (r^2 = 0.9153; n = 40), for both trees. Such empirical function is proposed as a first approximation for a transfer function between Rng and Qn. Thus, the main problem is to find an easy and reliable way to determine the tree leaf area. Problems with the Qn measuring system are discussed.*

Key words*: citrus, walnut, tree radiation balance, isolated tree, orchard.*

Resumo *-Dois conjuntos de dados de saldo de radiação de árvore isolada (Qn, MJ d^{-1}) foram analisados, sendo: um, para uma nogueira com 26,4m^2 de área foliar, em Palmerston North, Nova Zelândia; e outra, para uma lima ácida Tahití com 40m^2 de área foliar, cultivada num pomar em Piracicaba, SP, Brasil. Nas duas árvores os valores de Qn foram determinados por um sistema rotativo contendo saldo radiômetros (8 na nogueira, e 6 no citros) distribuídos eqüilatitudinalmente. O total diário de Qn "medido" foi obtido somando-se a contribuição de cada sensor ponderada pela fração de área de copa amostrada. Correlacionado-se Qn com o saldo de radiação obtido sobre grama na estação meteorológica (Rng, MJ m^{-2} d^{-1}) verificou-se que esta relação empírica foi uma função da área foliar das árvores (TLA), isto é, Qn foi diretamente proporcional à TLA, dentro do intervalo de área foliar usada. Fazendo-se Qn* = Qn / TLA (MJ m^{-2} de folha d^{-1}), sua correlação com Rng foi muito boa, gerando uma relação única do tipo Qn* = 0,32 (±0,02) Rng (r^2 = 0.9153; n = 40), para as duas árvores. Propõe-se que essa relação empírica seja utilizada como uma primeira aproximação de uma função de transferência entre Rng, que é facilmente medida, e Qn, de difícil medida. A dificuldade passa a ser a determinação rápida e confiável da área foliar das árvores. São discutidos os problemas encontrados com o sistema de medida de Qn.*

Palavras-chave: *citros, nogueira, saldo de radiação em árvore, pomar.*

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Introduction

One of the most difficult and limiting tasks in estimating either orchard or isolated tree transpiration is the determination of the absorbed net radiation. Field measurement is cumbersome because it is needed a set of net radiometers displayed around the tree. Besides the operational difficulties, the results represent only the sampled tree and cannot be taken to be representative of any other tree in the orchard. Presently, one has to either use special devices, such as that described by McNAUGHTON et al. (1992), to undertake the measurements or rely on theoretical models. In general, the available models are primarily concerned with interception of incoming solar radiation and this is only part of the overall absorbed net radiation.

Reported examples of field measurements are very few indicating the practical difficulties of such endeavor. THORPE (1978) used a static arrangement of 8 linear net radiometers set up around an imaginary cylinder enclosing apple trees in a hedge row orchard. McNAUGHTON et al. (1992), GREEN (1993), and GREEN & McNAUGHTON (1997) used a revolving circular structure (named "whirligig") envolving an isolated tree, where 8 regular net radiometers were mounted at equally spaced intervals on the circumference of the frame. The device rotated continually describing a sphere around the tree.

The objective here is to present a simple empirical approach to estimate the daily total net radiation absorbed by individual trees, either isolated or in orchards, based on the conventional grass surface net radiation measurements at the weather station and the tree leaf area.

Material and methods

Two sets of data were analyzed, being one extracted directly from the results reported by GREEN (1993) for an isolated walnut tree with 26.4m^2 of leaf area, near Palmerston North, New Zealand (40.2° S; 175.4° E) during 9 summer days (17-25/01/1992), using the "whirligig" rotating at 3.2 rpm. Another set was obtained using a similar device rotating at 3 rpm around an acid lime citrus tree (*Citrus latifolia* Tan.) in Piracicaba, SP (22° 42' S; 47° 38' W; 546 m), Brazil, and the results here reported were obtained during 31 days selected from December 1997 to March 1998, discarding rainy days. An automatic weather station located about 2km away from the citrus orchard gave the grass net radiation during the same period.

Initially, a whirligig apparatus similar to that described by McNAUGHTON et al. (1992) was built, but mechanical problems in the rotation system made its use very difficult without permanent assistance, and it was then decided to build a lighter version. The new system (Figure 1) consisted of three aluminum tube (1 ¼") circles of 3.3m in diameter tied orthogonally, being two in the vertical and one horizontally, to give a rigid structure capable of holding the sensors and the datalogger. The vertical circles were cut off at the bottom to allow room for the tree trunk, and a smaller horizontal circle (2.4m in diameter) was used to hold the whole structure in a stable position. This horizontal circle was also used as a support for the datalogger being necessary a counterweight. The apparatus was held in place by a 3.4m vertical steel pole (2 ½") with a 3m horizontal steel arm (2 ½"), and kept stable by three guiding wires. At the end of the arm there was a 1/6 HP electric driving motor. This new system can swing with the wind but during the measurements here reported swinging was not a problem.

Six new REBS Q7 net radiometers, available at the time, were used to measure the tree absorbed

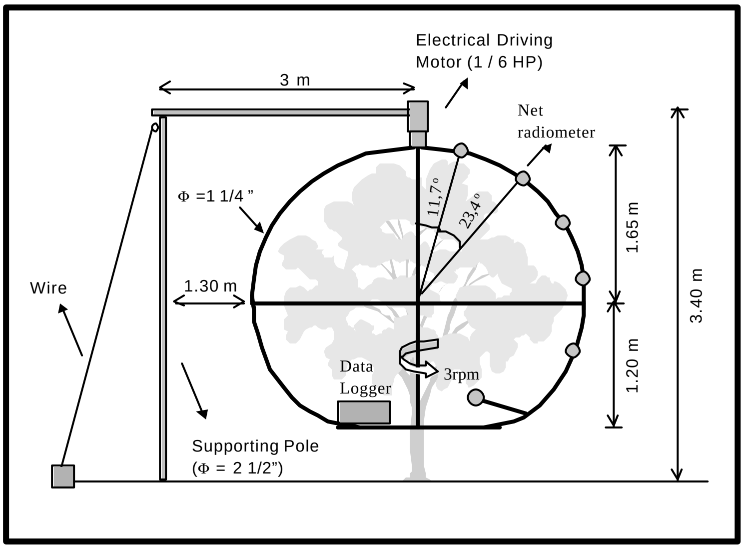

Figure 1. Scheme of the device used for the citrus tree net radiation measurements (Setup 2).

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net radiation. They were located with adaptation of the criteria suggested by McNAUGHTON et al. (1992) by placing them in a equilatitudinal distribution of 30° intervals with the first sensor at 15° from the vertical axis. There were three sensors in each hemisphere. The sensors were positioned about 0.3m from the vertical aluminum circle and about 0.1m above the foliage, to have a very narrow angle of view. The total integrating surface was equivalent to 34.21m^2 and the total net radiation Qn at a time was given by:

$$Qn = (0.067\ Rn_1 + 0.1828\ Rn_2 + 0.2506\ Rn_3 + 0.2506\ Rn_4 + 0.1828\ Rn_5 + 0.067\ Rn_6)\ 34.21 \quad (1)$$

being Rn_1, Rn_2, ..., Rn_6 the output of each sensor (Wm^{-2}); and the coefficients are the fractional sampled areas. Each sensor was sampled at every second and the data recorded by a CR10 Campbell datalogger, giving 15min averages. Equation (1) was multiplied by 900 to give the total net radiation during that time interval. The daily total Qn (MJ d^{-1}) resulted from the summation of all 15min averages starting at midnight.

After 15 days of measurement with this setup, it was detected during a clear sky morning that the lowest net sensor had its side facing the foliage exposed directly to the incoming solar radiation at some point during the revolution. The same problem occurred also in the afternoon showing that it was a symmetrical exposure to the direct solar radiation. Visual inspection showed that this direct radiation was not passing through the tree crown and as such it was not taking part in the radiation balance of the tree, and the sensor was afterwards moved to a horizontal position about 0.1m below the bottom of the foliage. The other sensors were then rearranged in a equilatitudinal display of 23.4° with the topmost one at 11.7° from the vertical axis. In this modified version there were four sensors in the upper and two in the lower hemisphere (Figure 1). Later analysis showed that, for this particular citrus tree, the contribution of the bottom sensor to the overall daily Qn was very small and the original distribution of sensors could well be kept since it is theoretically correct.

In the new setup, five sensors were placed tangent to an imaginary sphere enclosing the tree crown with the bottom sensor adjusted to sample the area of an imaginary circle below the foliage, resulting in a total integrating surface of 31.58m^2. The output of each sensor (Rn_1, Rn_2, … , Rn_6) was weighed by its new sampled fractional area, giving the following integrating expression:

$$Qn = (0.044\ Rn_1 + 0.126\ Rn_2 + 0.1873\ Rn_3 + 0.2174\ Rn_4 + 0.2117\ Rn_5 + 0.213\ Rn_6)\ 31.58 \quad (2)$$

The citrus tree was in a 7m x 8m spacing orchard, and it had to be pruned to fit inside the hoop, which was designed for a much smaller tree crown (it grew while the sensors were not yet available). Since pruning was necessary to fit inside the hoop it was decided to give it a spherical shape, more appropriate for the radiation measurements, but this is not a requirement for the method. If a larger hoop were used no pruning would be necessary as was the case with the walnut tree. It should be emphasized that the objective at that time was to “measure” the radiation balance of that particular citrus tree, testing McNAUGHTON et al. (1992) methodology. So, altering the tree shape was not a crucial problem. There was no concern in extrapolating the results to the other orchard trees. After pruning, the tree leaf area was determined to be around 40m^2, between January and mid-February, by sampling about 15 % of the leaves to determine the mean leaf area (= length x width x 0.71), which was then multiplied by total number of leaves on the tree (about 18,300 leaves). This value was assumed to be valid for the whole observational period because of the difficulties in determining tree leaf area frequently.

Results and discussion

At the onset of this discussion, it is important to analyze the effect of the sensors arrangement around the hoop, and the relative contribution of each sensor to the overall energy absorbed by the tree crown. It should be pointed out that the equilatitudinal setup (hereafter called setup 1), used at first, is theoretically sound because at the extreme situation, when no plant is inside the hoop, the symmetrical distribution of sensors is very likely to give a null output, as tested by McNAUGHTON et al. (1992), a condition which is less probable with the second arrangement here used. However, since the sampled citrus tree had very little porosity in its canopy (< 2 %), without sunflecks throughout the day, the modified setup (hereafter called setup 2) is not symmetrical but its results are believed to be reliable within the experimental error. The impelling factor for the setup change can be seen in Figure 2, which displays the time course of the net radiation for each sensor. It can be seen that sensor 6 (the lowest) gave a peak of Rn < -330 W m^{-2}, about three hours after sunrise, and this value is almost equal

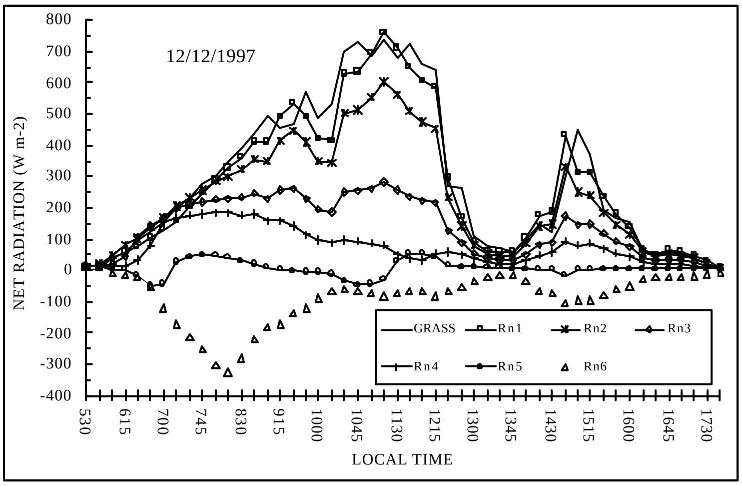

Figure 2. Time course of the non-weighed net radiation flux density for six sensors around the citrus tree with the equilatitudinal setup, and above grass net radiation.

to the positive output at the same time of the always unobstructed sensors 1 and 2 which were close to the top of the crown. The peak was less pronounced later in the afternoon and this attenuation was imposed by a taller eucalyptus windbreak in the direction of the sunset and by the occurrence of some sparse clouds. A visual inspection at the experimental site confirmed that such negative peak was caused by the incidence, during part of the revolution of sensor 6, of direct solar radiation which was not going through the foliage, that is, it was in error since such energy was not taking part in the crown radiation balance. Therefore, it was felt that such setup should be modified since the objective was to determine the total amount of radiant energy absorbed by that particular citrus tree. Large negative values (between –200 and –300 W m^{-2}) from the lower sensors were also obtained in the McNAUGHTON et al (1992), but they are for a tree with much small leaf area (10.6 m^2) and much large porosity (~ 0.4m^2 of leaves per m^3 of integrating crown) that permitted sun rays to go through it, a situation where the sensors arrangement is much more critical and the symmetrical setup is indeed more appropriate. This is not the case with more compact foliage (~2.1m^2 of leaves per m^3 of integrating crown), and wide base of the crown, as is the condition of the citrus tree here presented.

To check the effect of changing the sensors distribution around the tree, two days with similar amount of Qn and also with similar noontime solar elevation were selected. Day 1 (12/12/97), displayed in Figure 2, with setup 1 resulted in Qn = 154.83MJ d^1 and total sampled surface area equivalent to 34.21m^2, or 4.53MJ d^{-1} m^{-2} of integrating surface. Day 2 (13/01/98), had Qn = 148.68MJ d^1 with setup 2 and sampled area about 31.58m^2, or 4.71MJ d^1 m^{-2} of integrating surface. Thus, the two selected days had similar total input of net radiation and about the same solar trajectory. However, changing the sensors setup changed the relative contribution of each one because the same sensor, at different attitude, sampled different areas and radiation flux densities (Table 1). The upper hemisphere of the foliage accounted for over 85 % of the total daily absorbed energy in setup 1 (3 sensors covering 90°), while in setup 2 (4 sensors covering 93.6°) it represented about 94 % of Qn. But most of the radiation of sensor 4 (located at 81.9° from the zenith) comes from the upper hemisphere, and if it is accepted, for the sake of comparison, that at least half

Table 1. Sampled area and relative contribution of each sensor (in energy basis) to the overall 24 h net radiation absorbed by a citrus tree in two different sensors setups, in two days with equivalent net radiation input and solar trajectory throughout the day.

Sensor Number	Setup 1 (12/12/97)		Setup 2 (13/01/98)	
	Sampled Area (m^2)	% of total energy	Sampled Area (m^2)	% of total energy
1	2.29	16.2	1.39	11.7
2	6.25	37.7	3.98	28.8
3	8.57	31.5	5.98	30.2
4	8.57	17.8	6.87	22.9
5	6.25	2.0	6.69	8.3
6	2.29	-5.2	6.73	-1.9
Total	34.21	100.0	31.58	100.0

of its contribution comes from that hemisphere, then in setup 2 the upper hemisphere accounted for 82% of Qn, a figure not too different from that observed at setup 1.

Being responsible for the setup change, sensor 6 represented an average output of –41.3W m^{2} equivalent to –5 % of Qn in setup 1, and an average of -4.5W m^{-2}, or –2 % of Qn in setup 2. There were no completely overcast days without rain during the period of measurements with setup 1 and the above partitioning could not be done for days with low radiation balance. But with setup 2, for a day with Qn = 88.27MJ d^{-1}, sensor 6 represented an average output of –5.0W m^{-2}, or about –3 % of Qn. In regard to sensor 5, also in the lower hemisphere, its output represented about 2 % of Qn in setup 1, and increased to about 8 % in setup 2 (Table 1). At this time, it is difficult to conclude what introduced more error in the citrus experiment, if setup 1 with the incidence of direct solar beam at sensor 6, or the asymmetry of setup 2; however, the results indicate that the relative contribution of sensor 6 to the total Qn was very small in both setups.

It should be emphasized that the number of sensors (six) used in the citrus tree was dictated by the availability of net radiometers at the time of the experiment, but it is recognized that a larger number of sensors would be desirable, mainly for less compact and larger crowns. In regard to the hoop used, a "whirligig" similar to that described by McNAUGHTON et al. (1992) did not work as expected due to mechanical problems in the driving system, resulting in uneven rotation with different exposure time of the sensors. It is difficult to conclude which hoop system works better, but the lighter version can swing in windy conditions giving unreliable results; however, this was not the case here since the wind speed was always less than 3 m/s at a level near the top of the tree in the orchard.

McNAUGHTON et al. (1992) reported that the radiation absorbed (Qn, MJ d^{-1}) by a *Robinia pseudoacacia* tree was equivalent to eight times that measured over an uniform grass sward (Rng, MJ m^{-2} d^{-1}), or Qn = 8 Rng during an overcast day. Results shown in Figure 2 indicate that the Rng line was very close to those representing sensors 1 and 2. It can be seen also the effect of having Rng measured about 2 km away when some clouds appeared in the middle of the day. However, for that particular day, the discrepancy was not very large. Being Rng a fairly common measure in automatic weather stations the idea was then to correlate its daily total with the total Qn in an attempt to find an empirical transfer function. Using the citrus data, Figure 3 shows that Qn = 12.58Rng (r^2 = 0.8712; n = 31), on average. Some of the spread in the points can be attributed mainly to the asynchronous occurrence of clouds due to the distance between the orchard and the weather station (about 2km) as discussed before. Using the results reported by GREEN (1993), a different relationship was found, that is, Qn = 8.39Rng (r^2 = 0.9686; n = 9), but very close to that reported by McNAUGHTON et al. (1992). This is an indication that this kind of relationship is not unique but tree specific. In both sites, the range of Rng was similar (6 to 17.5MJm^{-2} d^{-1}), while Qn varied from 50 to 150MJ d^{1} in the walnut tree, and between 80 and 210MJ d^{1} in the citrus tree, both during the southern hemisphere summer. As the constant factor in the regression equations has dimension of m^2 of ground area, and Rng is expressed on unit area of ground covered by the grass, the relationships found indicate that, on average, the tree net radiation was equivalent to 12.58m^2 of ground covered with grass for the citrus, and to 8.39m^2 for the walnut tree. The small spread of the points confirms that the positioning of the lowest sensor had very little effect on the overall radiation balance of the citrus tree.

On average, the citrus tree absorbed about 1.5 (=12.58 / 8.39) times more radiation than the walnut tree, and this is primarily determined by the leaf area of each tree. Indeed, the citrus leaf area was

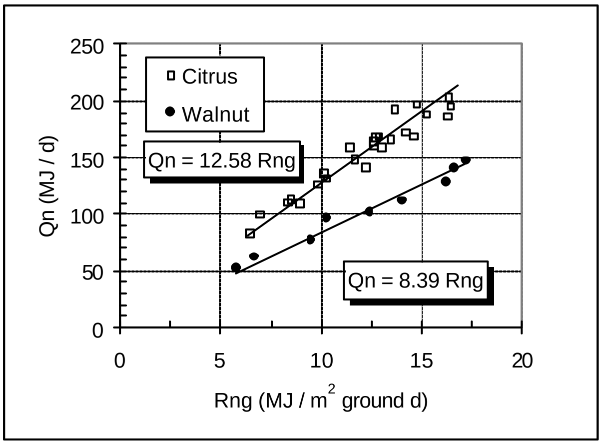

Figure 3. Relationship between measured daily total net radiation for the whole tree (Qn) and for the conventional grass surface (Rng).

1.52 (= 40 / 26.4) times larger than the walnut leaf area, which is the same ratio between the net radiation. If the absorbed net radiation is expressed on unit leaf area basis (Qn* = Qn / tree leaf area), then the amount of energy absorbed should be independent of the size of the exchanging surface in both situations. In fact, Qn* for both trees was equivalent to 32 ± 2 % of the standard grass net radiation ($Qn^* = 0.32$ Rng; $r^2 = 0.9153$; n = 40), and this seems to be a unique relationship (Figure 4). For the sake of estimating Qn this empirical relationship seems to be enough.

In the light of the approach here described it is not possible to accommodate the observation of McNAUGHTON et al. (1992) that a *Robinia pseudoacacia* tree with 10.6 m^2 of leaf area absorbed an equivalent of 8 m^2 of grass net radiation. According to the results here presented such relationship would be approximately 3.39 (= 0.32 * 10.6), and this is an indication that the problem of finding a transfer function to estimate Qn from routine weather station Rng is not yet solved, and further experimental measurements and analysis should be performed with trees of different sizes and crown porosities.

As transpiration takes place mainly during daytime, it was then compared daytime with 24 hours total for both Qn and Rng for the citrus tree site, resulting that, on average, $Qn_d = 1.06\ Qn_{24}$ and $Rng_d = 1.08\ Rng_{24}$.

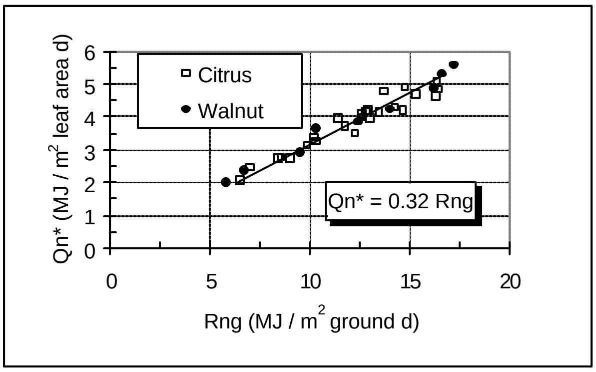

Figure 4. Relationship between tree net radiation, expressed on unit leaf area basis (Qn^*) and the conventional grass (Rng) net radiation

Conclusions

It was here inferred that the grass surface net radiation, as measured in standard weather stations, can be used to give reliable estimative of the total net radiation of isolated trees on a daily time scale. Even though only two small sets of data were analyzed, there is an indication that simply taking 32 ± 2% of the grass net radiation times the tree leaf area gives fairly good estimates of the daily total net radiation absorbed by an isolated tree. In practical terms, this empirical approach compensates for not having to use any special equipment, such as the “whirligig”, to “measure” the tree net radiation, which is then applicable only to that specific tree.

In regard to the arrangement of the net radiometers in the hoop, the symmetrical approach used by McNAUGHTON et al. (1992) should be preferred since it is theoretically sound and more appropriate for trees with sparse foliage.

Acknowledgement

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