SOLAR RADIATION ABSORPTION BY PLANT LEAVES

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Abstract

The aim of this research is to implement the model for solar radiation absorption by plant leaves to study the effects of season and time of the day on the absorbed amount of solar radiation. The effect of leaf area index, leaf angle distribution, leaf absorption coefficient were also considered. Calculations for the radiation flux densities for sunlit leaves, the radiation flux densities for shaded leaves, and the Absorbed total Photosynthetically Active Radiation on the leaves were carried out for Baghdad city (Latitude 33^{o} N). The results showed that the behavior of sunlit leaves and shaded leaves behave differently as season and time of the day change. The leaf parameters have significant effect on the amount of solar radiation absorbed by the leaves.

امتصاص الاشعاع الشمسي بواسطة اوراق النباتات

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المستخلص

ان الهدف من هذا البحث هو تطبيق انموذج امتصاص الاشعاع الشمسي من قبل اوراق النباتات لدراسة تأثير الموسم ووقت اليوم على كمية امتصاص الاشعاع الشمسي. تم الاخذ بنظر الاعتبار تأثير كلاً من معامل مساحة الورقة و توزيع زاوية الورقة و معامل امتصاص الورقة. ان حسابات كثافات فيض الاشعاع لاوراق النباتات المضاءة و وكثافات فيض الاشعاع للاوراق المضللة والاشعاع الكلي الفعال الممتص من قبل الاوراق قد اجريت في مدينة بغداد (خط عرض 33^{o} N). دلت النتائج ان سلوك الاوراق المضاءة والمضللة يكون مختلف مع اختلاف الفصل ووقت اليوم. ان معاملات الورقة يكون لها تأثير هام في كمية الاشعاع الشمسي الممتص من قبل الاوراق.

Introduction

Information about total, direct and diffuse Photosynthetically Active Radiation (PAR) is required in simulation models to estimate carbon gain and growth of vegetation. While there are existing worldwide networks of stations where direct, diffuse and reflected global radiation are measured using standardized instrumentation and methodology (World Radiometric Reference; Romero et al., 1996). No such network exists for PAR.

The use of either physical spectral or parameterized models to estimate PAR has been addressed by several authors, especially Gueymard (1989) [1] and Alados et al. (2002) [2]. Spectral models provide an estimate of the different components of solar spectral irradiance and by spectral integration, photosynthetic photon flux density under cloudless conditions (SPECTRAL2, [3]; SMARTS2, [4]). However, while soundly based in a theoretical sense, such spectral models are of extreme computational complexity, and often require very specific input data which are rarely available in practice (e.g., spectral optical characteristics of aerosols). As a compromise, parametric models have been proposed to obtain an accurate, versatile and non-climate specific estimate for solar radiation. This type of model is based on the same physical principles as the spectral models, but strongly simplifies estimation procedures with a set of parameterizations dependent on preliminary integration of spectral transmittance functions and sensitive to the most important extinction sources of the atmosphere (CPCR2, [5]; PAR MODEL, [6]; the model of Alados-Arboledas et al., 2000 [7]). The application of parametric models allows study of PAR directly as well as the relationship of PAR to global radiation. A sensitivity analysis examining factors that potentially influence the relationship between global radiation and PAR by Gonzalez and Calbo (2002) [8] suggests that air mass and precipitable water vapor are of primary interest, followed by turbidity, whereas ozone and ground albedo play a minor role. This research aims at investigating the behavior of solar radiation through plant canopies during different seasons and different times during the day. The effects of leaf area index, leaf angle distribution, leaf absorption coefficient are also considered.

The Model

The propagation of solar radiation through plant canopies is assumed follows Beer's law. There are two components of radiation arriving at the top of the plant canopy. Leaves in the canopy are either sunlit or shaded. The radiation flux density can be modeled as follows [9].

$$Q_{Sunlit} = K_b(\psi) S_b + Q_d + Q_S \qquad (1)$$

$$Q_{Shaded} = Q_d + Q_S \qquad (2)$$

where $K_b(\psi)$ is the light extinction coefficient for direct radiation when the sun is at zenith angle ψ. S_b is flux density of solar radiation on a horizontal surface. Q_d is the average diffuse radiation flux density on the leaves and Q_s is scattered direct radiation.

For leaves with absorptance α, the beam radiation at the bottom of a plant canopy is:

$$Q_{bt} = S_b \exp\left[-K_b(\psi)\sqrt{\alpha L}\right] \qquad (3)$$

where L is total leaf area index of plant canopy. $K_b(\Psi)$ is a function of leaf angle distribution, and the solar zenith angle as follows [10]:

$$K_b(\psi) = \frac{\sqrt{X^2 - \tan^2(\psi)}}{X + 1.774\left(X + 1.182\right)^{-0.722}} \qquad (4)$$

For spherical leaf angle distribution, x=1, for vertical leaf angle distribution, x=0, and for horizontal leaf angle distribution, x approaches infinity.

If the leaves absorb all radiation at its surface, i.e. α=1, the direct radiation at the bottom of the canopy [10]:

$$Q_b = S_b \exp\left[-K_b(\psi) L\right] \qquad (5)$$

The difference between Q_{bt} and Q_b is the scattering of direct radiation at the bottom. Assuming there is no scattering of direct radiation at the top of the canopy, the mean flux density of scattering direct radiation of the leaves can be modeled as:

$$Q_S = \left(Q_{bt} - Q_b\right)/2 \qquad (6)$$

The diffuse radiation intensity at the bottom of the canopy is

$$Q_{dt} = S_d \exp\left[-K_d(\psi)\sqrt{\alpha L}\right] \qquad (7)$$

However, S_d and Q_{dt} cannot simply be averaged to get the average diffuse radiation flux density on the leaf surface. Because radiation decreases exponentially through the canopy, the actual average diffuse radiation flux density is

$$Q_d = \frac{S_d\left[1 - \exp\left(-K_d(\psi)\sqrt{\alpha L}\right)\right]}{K_d\sqrt{\alpha L}} \qquad (8)$$

Where K_d is the extinction coefficient for diffuse radiation.

The extinction coefficient for diffuse radiation, K_d, has to be calculated numerically. Because the diffuse radiation can enter the forest canopy from all directions in the upper hemisphere, the transmittance of diffuse radiation is [11]:

$$\tau_d = \int_0^{\frac{\pi}{2}} \tau_b(\psi)\sin(2\psi)\, d\psi \qquad (9)$$

where

$$\tau_b(\psi) = \exp\left[K_b(\psi)\right] \qquad (10)$$

Based on Beer's Law

$$\tau_d(\psi) = \exp\left[K_d\sqrt{\alpha L}\right] \qquad (11)$$

K_d can be calculated from equations 9 and 11.

Methodology

(Figure 1) shows the block diagram for the implementation of the model. The first two steps are to define the model variables and setting the parameters. The model requires calculation of the solar zenith angle. In this work the solar position algorithm of Reda and Andreas (2008) [12] was used to determine the solar zenith angle as a function of the hour angle. The direct and diffuse components of solar radiation were calculated by using the model suggested by Muneer (2004) [13]. The calculations of the last three steps in the block diagram were performed by using the formulations discussed in the previous section.

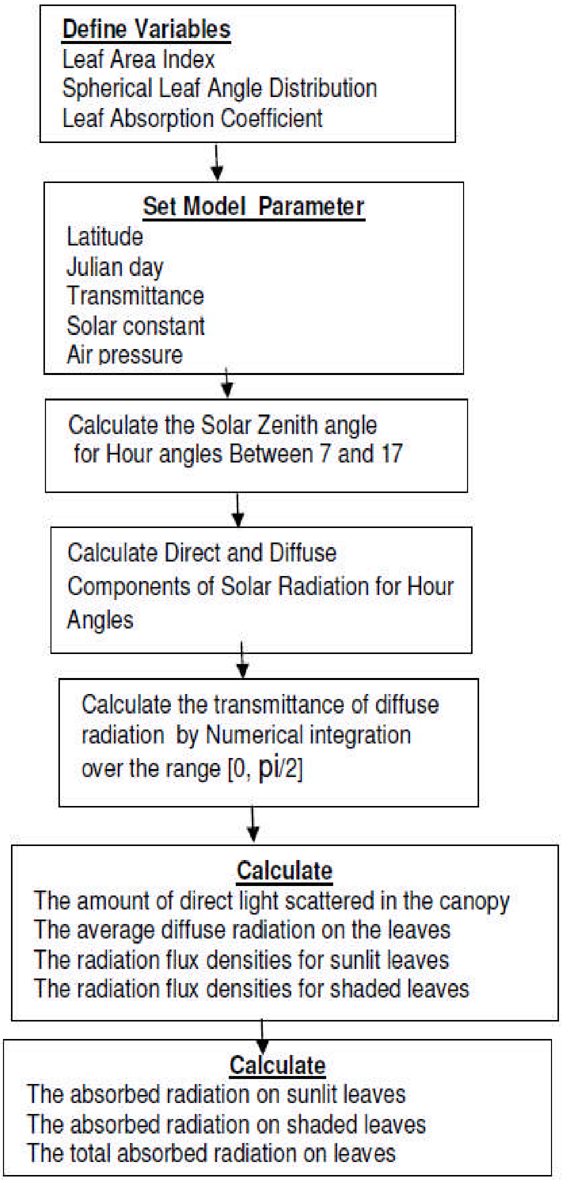

Figure 1: Block diagram of the model for calculating solar radiation absorption by leaf.

Results and Discussion

Calculations for the radiation flux densities for sunlit leaves (Sunlit), The radiation flux densities for shaded leaves (Shaded) , and the Absorbed total Photosynthetically Active Radiation (APAR) on the leaves for different seasons and different times during the day for Baghdad city (Latitude 33^o N).

(Figure 2) shows Sunlit, Shaded, and APAR for January, March, June, and September which they represent winter, spring, summer, and fall seasons respectively. It is obvious that the peak value of Sunlit occurs at noon for all seasons and the maximum peak occurs during the summer season and the minimum peak occurs during the winter season. The values of the Sunlit peaks during spring and fall seasons are comparable. These behaviors are consistent with the behavior of incident direct radiation because Sunlit depends on the direct incident solar radiation. Shaded is almost constant during the seasons and the time of the day. The APAR is identical to that of Sunlit since APAR is the sum of Sunlit and Shaded. In Figures 3 to5 summer seasons is assumed in the calculations.

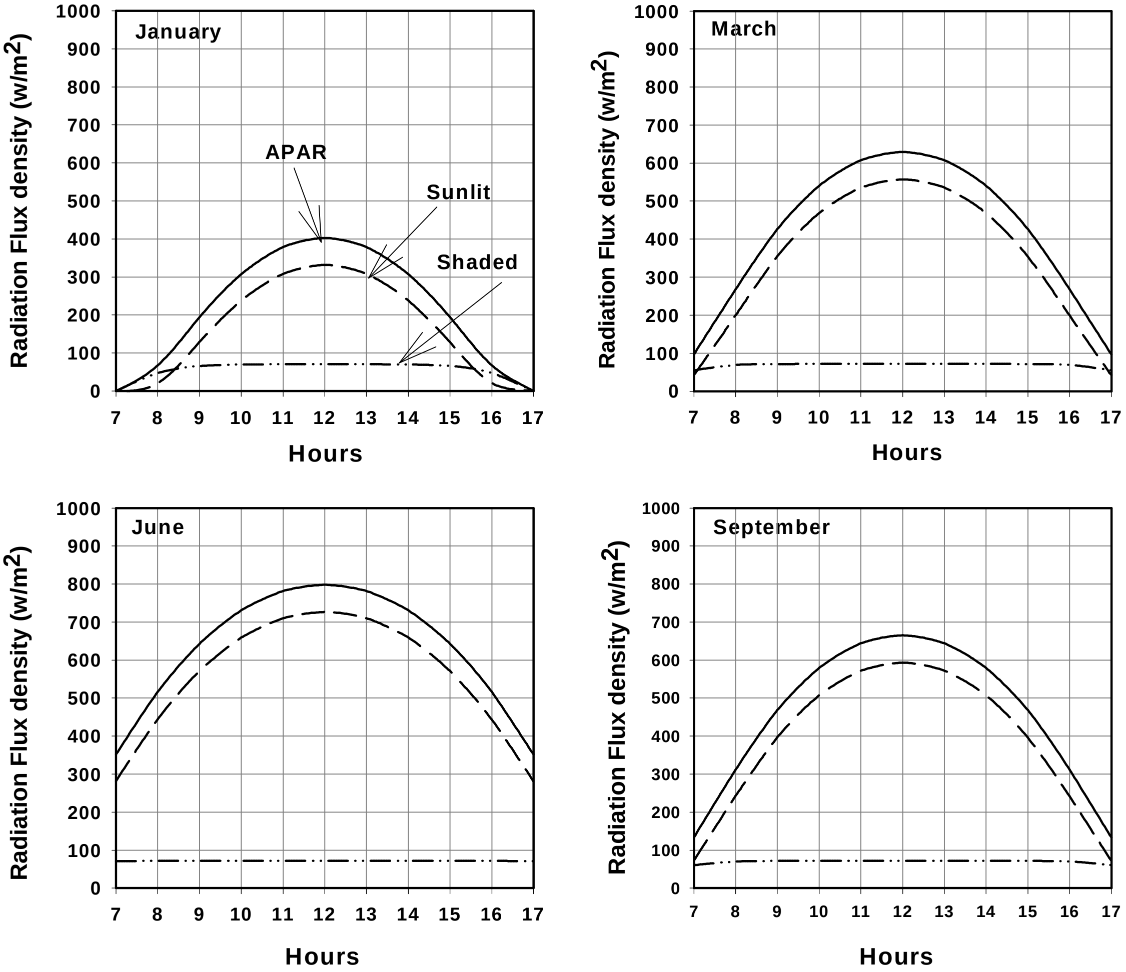

Figure 2: Radiation flux density for sunlit, shaded leaves and their sum (APAR) as a function of time of the day for January, March, June, September at Baghdad (33^{o} N) assuming LAI=1, x = 0 and a=0.85

(Figure 3) illustrated the effects of Leaf Area Index (LAI), It is seen that Sunlit increase with increasing LAI while the behavior of Shaded is quite different for each LAI value. For small LAI, Shaded assumes relatively small values and decreases gradually from sunrise to noon and then increases towards sunset. The behavior of Shaded at large LAI is the opposite of that for small LAI values. It assumes relatively large values and tends to increase from sunrise to noon and then decreases from noon to sunset. For moderate values of LAI, shaded is almost constant. The behavior of APAR is similar to that of Shaded. (Figure 3) shows the results for the effects of leaf angle distribution. Three distributions were assumed, namely: vertical (x=0); spherical (x=1); and more horizontal (large x, e.g. x=5). It is seen that for both Sunlit and Shaded have higher values on the more horizontal leaves and smaller values on vertical leaves. Sunlit increases with increasing the behavior of Sunlit for more horizontal and spherical leaves increases from sunrise to noon and then decreases towards sunset. For vertical leaves, Sunlit has two identical peaks around 8:30 and 15:30 and has a minima at noon. This is because of the variations of solar altitude during the day, i.e. the sun is just overhead at noon. (Figure 4) presents the results for the effect leaf absorption coefficient. It is seen Sunlit, Shaded, and APAR increases with increasing the absorption coefficient of the leaf.

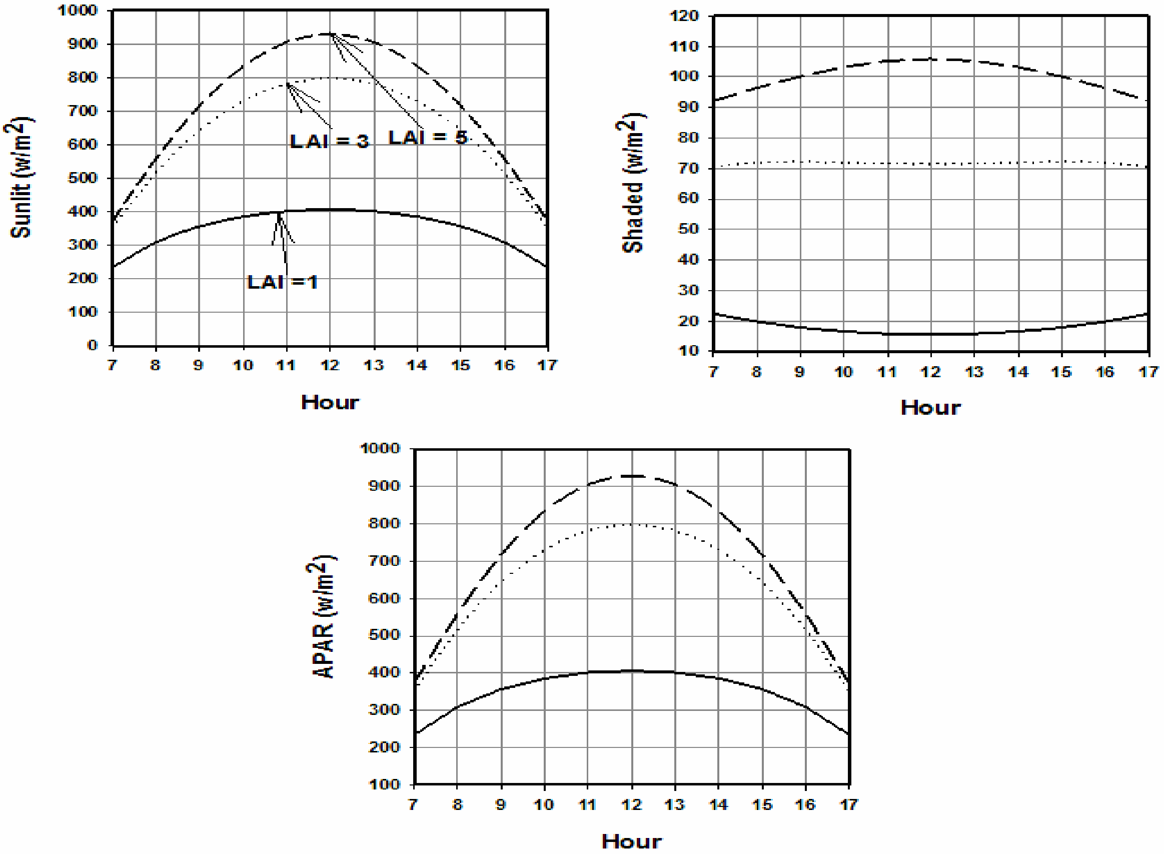

Figure 3: Radiation flux density for sunlit, shaded leaves and their sum (APAR) as a function of time of the day for different LAI at Baghdad (33^o N) assuming, month=June, x = 0, and a=0.85.

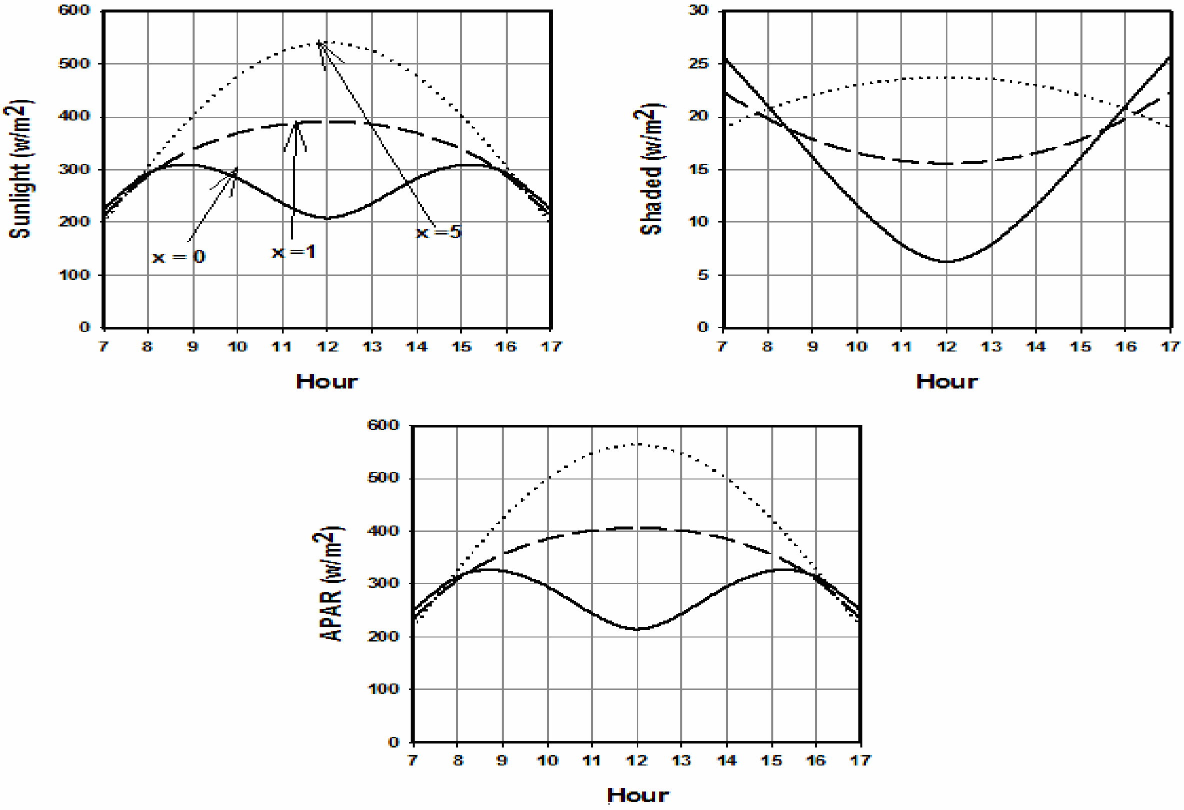

Figure 4: Radiation flux density for sunlit, shaded leaves and their sum (APAR) as a function of time of the day for different x at Baghdad (33^o N) assuming, month=June, LAI =1, and a=0.85.

Conclusions

In this research, radiation flux densities for sunlit leaves, the radiation flux densities for shaded leaves, and the Absorbed total Photosynthetically Active Radiation on plant leaves for different seasons and different times during the day for Baghdad city (Latitude 33° N) were calculated. The effects of leaf area index, leaf angle distribution, and leaf absorption coefficient were investigated. The results indicated that all each of these parameters plays an important role the amount of solar radiation absorbed by plant leaves.

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