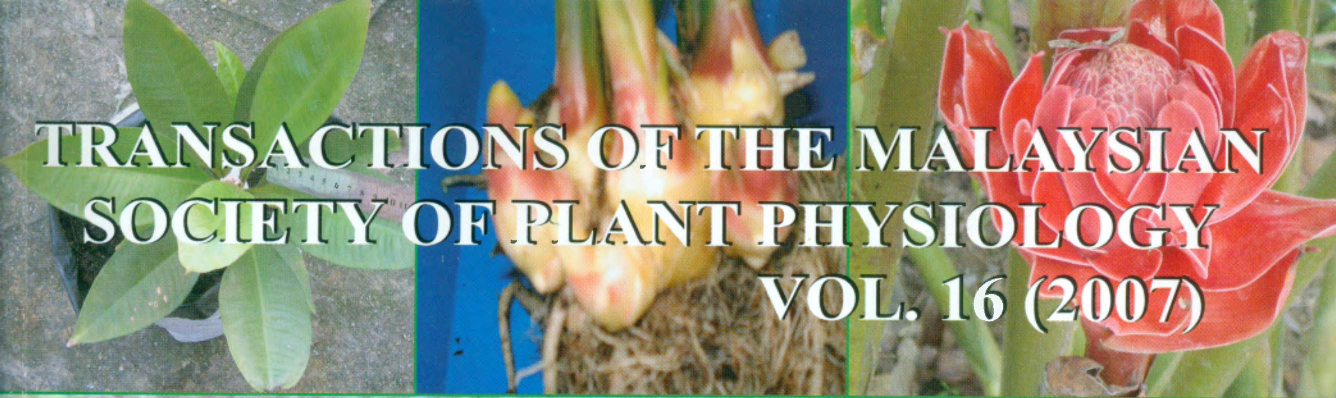

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YIELD AND QUALITY ENHANCEMENT OF PLANT

HAWA ZE JAAFAR (EDITOR-IN-CHIEF)
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Hawa ZE Jaafar (Editor-in-Chief)
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EQUATIONS TO ESTIMATE THE INTERCEPTION OF DIRECT AND DIFFUSE LIGHT BY DISCONTINUOUS CANOPIES

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ABSTRACT

Beer's law is often used to estimate the amount of light intercepted by plant canopies. Nonetheless, Beer's law assumes that the plant canopies are continuous or closed, and cannot be applied for sparse or discontinuous canopies. The objective of this study was thus to modify Beer's law so that it could be applied for discontinuous canopies. This was done by introducing a canopy clumping factor that ranges from 0 to 1, where smaller values indicate larger exposed areas of the ground, and a maximum value of 1 indicates full ground cover by the canopies. Two equations were developed: one to estimate the interception of direct light and another diffuse light by the canopies. This paper presents these equations and how they were each derived.

INTRODUCTION

Light is a major source of energy to plants. It drives several vital processes in the plant such as photosynthesis, transpiration and water uptake. Consequently, determining the amount of light intercepted by plant canopies is often of great interest. Assuming no light reflection and scattering, the amount of light intercepted by plant canopies is simply the difference between the irradiance above and below the canopies. However, in the absence of any physical measurements, the irradiance below the canopies can be estimated, often using Beer's law which is

$$I = I_0 \exp(-kL) \tag{1}$$

where I_0 and I are the solar irradiance (W m^{-2}) above and below the canopies, respectively; k is the canopy extinction coefficient (unitless; its value ranges from 0 to typically 1); and L is the leaf area index (m^2 leaf area m^{-2} ground area). The amount of light intercepted by the plant canopies, I_p, is thus

$$I_p = I_0 - I_0 \exp(-kL) = I_0 \left[1 - \exp(-kL)\right] \tag{2}$$

Nonetheless, Beer's law assumes that the canopies are continuous (*i.e.*, closed canopies). This means that Eq. 1 and 2 are only applicable when the ground is fully covered by the canopies. Open or discontinuous canopies such as in sparse plant planting (*i.e.*, low planting density) or when the plant canopies are still small (*i.e.*, young plants) violates the assumption of Beer's law. This violation causes Beer's law to underestimate the irradiance below the canopies, which in turn, overestimates the amount of light interception by the plants.

Consequently, the objective of this paper is to show how Beer's law was modified to produce two simple equations to estimate the amount of light interception by discontinuous canopies.

THEORY: DEVELOPMENT OF THE EQUATIONS

Total incoming irradiance, I_0, consists of two components: direct ($I_{0,dr}$) and diffuse ($I_{0,df}$) irradiance, which means that

$$I_0 = I_{0,dr} + I_{0,df} \tag{3}$$

Direct light comes from a single direction, whereas diffuse light comes from all directions. Consequently, the equations to estimate the amount of interception of direct and diffuse light will be treated separately.

Direct light interception

The method by Jackson and Palmer (1979) is adapted. Direct light transmission through a discontinuous canopy τ_{dr} consists of two separate and additive components: a component that traverses through the canopy, and the other that does not (Figure 1), or

$$\tau_{dr} = \tau_b + \tau_c \tag{4}$$

where τ_b is the fraction of light reaching the ground without having to traverse through the canopy; and τ_c is the fraction of light passing through the canopy. (1-τ_b) is the fraction of ground covered by the canopies. It can be estimated simply as the ratio between the actual leaf area index (LAI) and the LAI for maximum ground cover. Typically, maximum ground cover is achieved when LAI = 3, so this means that

$$(1-\tau_b) = \begin{cases} L/3 & \text{for } L < 3 \\ 1 & \text{for } L \geq 3 \end{cases} \quad \text{or} \quad \tau_b = \begin{cases} 1-L/3 & \text{for } L < 3 \\ 0 & \text{for } L \geq 3 \end{cases} \tag{5}$$

Leaf area index is the total leaf area in 1 m^2 ground area. However, in discontinuous canopies, the leaf area is not evenly spread out over the ground, but is clustered or clumped in a (1-τ_b) fraction of a 1-m^2 ground area. Consequently, the adjusted or effective leaf area index L' is

$$L' = L/(1-\tau_b) \tag{6}$$

As shown in Figure 1, τ_c has a maximum value of (1-τ_b) if the canopy is completely transparent, but if it is not, then this maximum transmission value (1-τ_b) will decrease exponentially according to Beer's law as

$$\tau_c = (1-\tau_b)\exp[-k_{dr}L'] = (1-\tau_b)\exp[-k_{dr}\, L/(1-\tau_b)] \tag{7}$$

where k_{dr} is the canopy extinction coefficient for direct light. Substituting Eq. 7 into Eq. 4 gives the total fraction of solar radiation reaching the ground as

$$\tau_{dr} = \tau_b + (1-\tau_b)\exp\left[-k_{dr}\, L/(1-\tau_b)\right] \tag{8}$$

However, Eq. 8 is only valid when the Sun is directly above the canopies (*i.e.*, at zenith angle, $\theta = 0°$). When the solar beams arrive at an angle $\theta > 0°$, the total fraction of solar beams reaching the ground will be lesser than that predicted by Eq. 8 because these solar beams have a longer path to travel and reach the ground. The longer the path, the greater the probability that the beams would be intercepted by the canopies.

A clump factor ω (a value between 0 and 1) is introduced into Beer's law to account for discontinuous canopies:

$$\tau_{dr} = \exp\left(-k_{dr}\omega L\right) \tag{9}$$

Substituting Eq. 8 into Eq. 9, the clump factor when the Sun is at zenith is determined by

$$\omega_0 = -\ln\left\{\tau_b + (1-\tau_b)\exp\left[-k_{dr}\, L/(1-\tau_b)\right]\right\}/k_{dr}L \tag{10}$$

where ω_0 is the maximum clump factor value, achieved when the solar inclination is at zenith ($\theta = 0°$). With increasing solar inclination, the path length of solar beams increases; thus, decreasing the clump factor. The question now is really how to describe this declining trend. It is assumed that the clump factor varies exponentially with solar inclination as

$$\omega = b_0 \exp\left(b_1\theta\right) \tag{11}$$

where b_0 and b_1 are constants. When $\theta = 0°$, $\omega = \omega_0$, so this means that the constant $b_0 = \omega_0$. When the clump factor ω is 1, Eq. 9 is equivalent to Eq. 1 and that there is no effect of discontinuous canopies. With increasing solar inclination, the probability of a solar beam reaching the ground without having to traverse through a canopy decreases. At maximum inclination ($\pi/2$), this probability is zero. Hence, ω is taken as 1 when θ is $\pi/2$, so the constant $b_1 = (2/\pi)\ln(1/\omega_0)$ which gives

$$\omega = \omega_0 \exp\left[\frac{2\theta}{\pi}\ln\left(\frac{1}{\omega_0}\right)\right] = \omega_0^{\,1-2\theta/\pi} \tag{12}$$

Most plants do not show any preferential leaf orientation (Goudriaan & van Laar 1994). This means that most plants have leaves that are oriented in all directions uniformly. Such leaf distribution is known as the random, uniform or spherical leaf orientation. In this orientation, the canopy extinction coefficient for direct light, k_{dr}, is dependent solely on the solar inclination θ as

$$k_{dr} = 0.5/\cos\theta \tag{13}$$

Thus, from Eq. 2, 9, 12 and 13, the amount of direct light intercepted by plant canopies, $I_{p,dr}$, is

$$I_{p,dr} = I_{0,dr}\left[1-\exp\left(\frac{0.5}{\cos\theta}\cdot\omega_0^{\,1-2\theta/\pi}\cdot L\right)\right] \tag{14}$$

where $I_{0,dr}$ is the irradiance of the direct component above the canopies; and ω_0 is from Eq. 10.

Diffuse light interception

As shown by Campbell and Norman (1998), and Teh (2006), the ratio between the diffuse irradiance below and above the canopies, τ_{df}, is

$$\tau_{df} = 2\int_0^{\pi/2}\exp\left(-k_{dr}L\right)\cos\theta\sin\theta d\theta \tag{15}$$

Eq. 15 was obtained by assuming a uniformly bright sky. For discontinuous canopies with random leaf orientation, Eq. 15 is modified to

$$\tau_{df} = 2\int_0^{\pi/2}\exp\left(-\frac{0.5}{\cos\theta}\cdot\omega_0^{\,1-2\theta/\pi}\cdot L\right)\cos\theta\sin\theta d\theta \tag{16}$$

Following Beer's law (Eq. 2), the irradiance of the diffuse component below the canopies, I_{df}, is

$$I_{df} = I_{0,df}\exp\left(-k_{df}L\right) \tag{17}$$

where $I_{0,df}$ is the irradiance of the diffuse component above the canopies; and k_{df} is canopy extinction coefficient for diffuse light. Since τ_{df} is the ratio between the diffuse irradiance below and above the canopies, the following equation is analogous to Eq. 15:

$$\begin{aligned}\tau_{df} &= I_{df}/I_{0,df} = \exp\left(-k_{df}L\right)\\ \therefore k_{df} &= -\ln\left(\tau_{df}\right)/L\end{aligned} \tag{18}$$

The relationship between k_{df} and L was established by setting L to a reasonable value in Eq. 15, and it was integrated numerically to solve for τ_{df}. Substituting τ_{df} and its corresponding L value into Eq. 18, k_{df} is subsequently solved. By repeating these steps several times (but using different values of L for each step), the relationship between k_{df} and L was obtained (Figure 2). The empirical equation to calculate k_{df} from L was determined as

$$k_{df} = \frac{0.6936+13.2910L^2-2.3648L^4+0.1701L^6}{1+22.6522L^2-4.0257L^4+0.2674L^6} \tag{19}$$

where the degree of equation fit R^2 = 0.9836 and with all of the equation coefficients statistically significant ($p < 0.05$).

The equation to determine the amount of diffuse light intercepted by plant canopies, $I_{p,df}$, is thus

$$I_{p,df} = I_{0,df}\left[1-\exp\left(-k_{df}L\right)\right] \tag{20}$$

where k_{df} is determined from Eq. 19. Further simplification of Eq. 20 is possible. Figure 3 shows the strong linear relationship between the multiplicative ($k_{df}L$) and L, where their relationship is empirically determined as

$$k_{df}L = 0.03 + 0.6535L \tag{21}$$

with a degree of fit $R^2 = 0.9953$. Thus, Eq. 20 is finally re-expressed to

$$I_{p,df} = I_{0,df}\left[1-\exp\left(-0.03-0.6535L\right)\right] \tag{22}$$

RESULTS AND DISCUSSION

Kustas and Norman (1999) gave the dependence of clump factor on solar inclination as

$$\omega = \frac{\omega_0}{\omega_0 + (1-\omega_0)\exp\left[-2.2\theta^{3.8-0.46D}\right]} \tag{23}$$

where D is the ratio between the plant height and width; and ω_0 is from Eq. 10. Eq. 12 was tested against Eq. 23, and it obtained good accuracy for various LAIs and canopy dimensions (D). Figure 4 shows the fraction of solar beams reaching the ground, as estimated using the clump factor in Eq. 12 and 23. Comparisons shown in Figure 4 were for a spherical leaf distribution, LAI = 1, and $D = 2$.

This work is still ongoing where further tests are required to measure the accuracy of the equations against field measurements.

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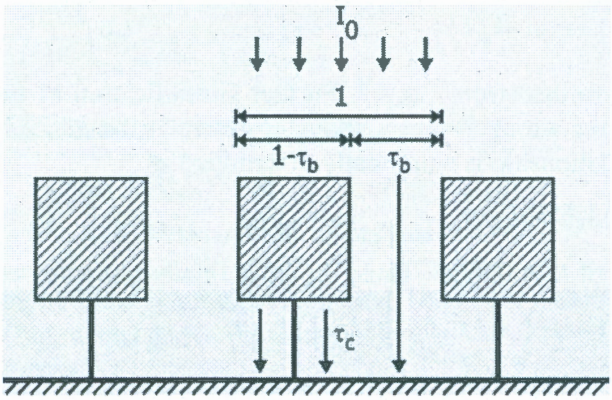

Figure 1. Discontinuous canopies violate one of the assumptions of Beer's law which require a uniform distribution of canopies (after Jackson & Palmer 1979).

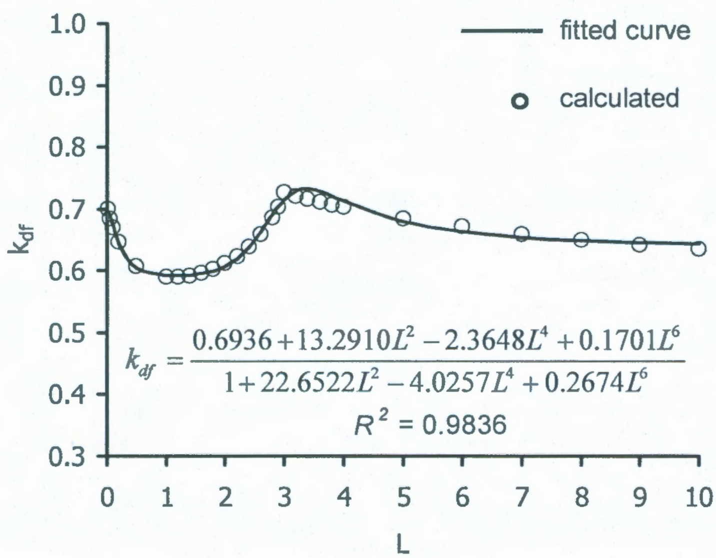

Figure 2. Relationship between the canopy extinction coefficient for diffuse light, k_{df}, and leaf area index, L.

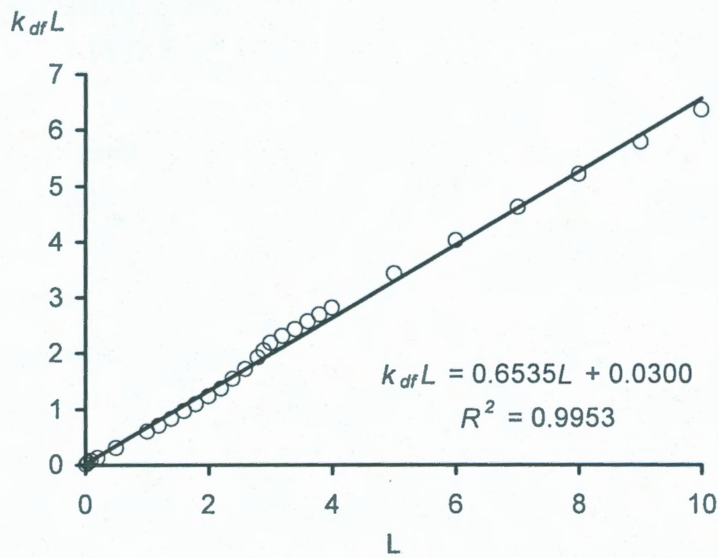

Figure 3. Relationship between ($k_{df}L$) and L.

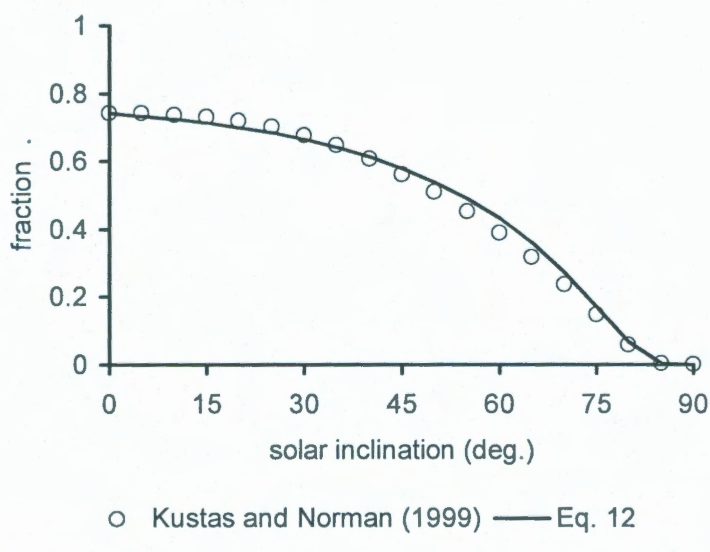

Figure 4. The fraction of solar beams reaching the ground using the clump factor as estimated by Kustas and Norman (1999) and by Eq. 12.