Estimating the Absorptivity of Solar Radiation in Soybean Canopies — for Use in Crop Models —

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Abstract

The equation of Monsi and Saeki (1953) has often been used in crop growth models to calculate the transmittance (Ą) of radiation using a constant value of the extinction coefficient (k) throughout a growing season. However, there are some questions about the above usage. One purpose of this study is to examine the applicability of the equation to crop growth models. The other purpose of this study is to find a simple equation to estimate the radiation absorptivity (ƒ¿), because calculation of ƒ¿ usually requires some determinants that are difficult to obtain.

Ą and canopy reflectivity (r) were measured in experimental plots, and the following results were obtained. The equation of Monsi and Saeki (1953) successfully related daily mean Ą and LAI using a constant value of k throughout a growing season regardless of the row direction, planting density or radiation intensity. Therefore, the general applicability of the equation for crop growth models was confirmed.

The following equation to calculate ƒ¿ was derived and verified experimentally:

\[ ƒ¿ = C \cdot (1 - r_t) \]

where \( r_t \) is the reflectivity of a fully closed canopy.

It was also confirmed that the coverage (C) can be used to approximate \( (1 - Ą) \). Then, ƒ¿ can be calculated using C:

\[ ƒ¿ = C \cdot (1 - r_t) \]

Key words: Absorptivity, Fractional interception, Reflectivity, Solar radiation, Transmittance.

1. Introduction

The proportional relationship between the amount of intercepted solar radiation and the biomass production by a crop canopy has long been known (Shibles and Weber, 1965; Williams et al., 1965; Baker and Meyer, 1966; Monteith, 1977). Growth analysis and simulation models using the above relationship were recently proposed (MaacKerron and Waister, 1985; Sinclair, 1986; Russel et al., 1989). In some studies (e.g., Hirota and Takeda, 1978; Horie and Sakuratani, 1985), Absorbed radiation was used instead of intercepted radiation. These two are different, as Gallagher and Biscoe (1978) and Gallo and Daugtry (1986) pointed out, and absorbed radiation is more appropriate for the analysis and prediction of crop growth because reflected loss is ignored in intercepted radiation.

Absorbed radiation (\( R_a \)) is calculated as:

\[ R_a = R_s \cdot ƒ¿ \]

where \( R_s \) is the solar radiation and ƒ¿ is the absorptivity of the canopy. In crop growth models, ƒ¿ affects the biomass production linearly, and precise estimation of ƒ¿ is essential. ƒ¿ is calculated by the following equation (e.g., Kishida, 1973):

\[ ƒ¿ = 1 - r - (1 - r_0) \cdot τ \]

where \( r \) is the reflectivity of a canopy surface, \( r_0 \) is the reflectivity of the soil surface beneath the canopy, and \( τ \) is the transmittance, respectively. Estimation of ƒ¿ based on equation (2) will be discussed in this paper for use in crop growth models.

The following equation, derived from Beer's
Law (Monsi and Saeki, 1953), is often used to describe the vertical profile of light intensity in a canopy:

$$\tau = \exp(-k \cdot LAI)$$  

where $k$ is the extinction coefficient and $LAI$ is the leaf area index (the ratio of leaf area to ground area). $k$ changes depending on such factors as the condition of incident light and the position of the individual leaves in the canopy (Kuroiwa and Monsi, 1963). However, detailed examination of the effects of these factors is beyond the purpose of this study. Daily mean $\tau$ is sufficient for many crop growth models. It is very convenient if equation (3) can be used to calculate daily mean $\tau$ with a constant value of $k$ throughout a growing season regardless of growth stage, row direction, planting density, or the weather. However, there are several questions about this usage. First, crops are usually planted in rows and thus form discontinuous canopies. The structure of the canopy (e.g., foliage shape and leaf area density) changes as it grows. Oikawa (1977) and Kokubun (1981) showed that the canopy structure affects the light environment of a canopy. Therefore, the value of $k$ in equation (3) will change as the canopy grows. Secondly, Baker and Meyer (1966), Allen (1974), and Kurata et al. (1988) showed that the row direction affects the canopy light environment. This indicates that $k$ can be affected by the row direction. Finally, Kuroiwa and Monsi (1963), and Hipps et al. (1983) showed that the light environment of a canopy changes depending on the condition of the incident light; therefore weather (represented by the radiation intensity) can affect $k$. The applicability of equation (3) using a constant value of $k$ throughout a growing season therefore must be examined before applying it to growth models.

There is another problem in calculating the absorptivity of a canopy. The values of $r$ and $r_0$ are required when $\alpha$ is calculated by equation (2). This makes the equation difficult to use because determining $r$ is cumbersome and measuring $r_0$ is particularly difficult. A simple equation to calculate $\alpha$ without $r$ and $r_0$ is needed.

The purpose of this study is to examine the practical applicability of equation (3), and to derive and verify a simple equation to calculate $\alpha$, for use in crop growth models to calculate biomass production.

2. Materials and methods

2.1 Cultivation

The experiment was conducted at the research farm of the National Agriculture Research Center in Tsukuba (lat. 36°01'N, long. 140°07'E, 25 m above sea level, volcanic ash soil). Soybeans (Glycine max L. cv. Enrei) were grown in 1986, 1987 and 1988. The sowing dates, row directions, and planting densities are summarized in Table 1. Soybeans were planted in rows with inter-row spacings of 0.6 m. The plant spacing ranged from 0.05 m to 0.25 m, which provided planting densities from 6.7 to 33.3 plants·m⁻². Before sowing 30 kg ha⁻¹ of nitrogen, 100 kg ha⁻¹ of phosphoric acid and 100 kg ha⁻¹ of potassium were applied in all plots. The soybeans were chemically protected against pests and disease.

<table>
<thead>
<tr>
<th>Year</th>
<th>Sowing date</th>
<th>Row direction</th>
<th>Planting density (plants·m⁻²)</th>
<th>Row spacing (m)</th>
<th>Plot size (m x m)</th>
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</thead>
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<tr>
<td>1986</td>
<td>Jun 3</td>
<td>SW-NE</td>
<td>33.3</td>
<td>0.6</td>
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</tr>
<tr>
<td>1986</td>
<td>Jun 3</td>
<td>SW-NE</td>
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<td>0.6</td>
<td>8 x 11</td>
</tr>
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<td>July 7</td>
<td>SW-NE</td>
<td>33.3</td>
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<tr>
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<td>8.3</td>
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<td>SW-NE</td>
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<td>0.6</td>
<td>5 x 13</td>
</tr>
</tbody>
</table>

2.2 Measurements

Global solar radiation on a horizontal surface was measured with an Eppley pyranometer (EKO MS42). Tube-type pyranometers were placed on the ground as illustrated in Fig. 1 to measure the radiation transmitted through the canopy. Reflected radiation from a canopy surface was measured in 1986 by a Noshi-Denshi solarimeter or a tube-type pyranometer (EKO MS33) set upside down at a height of 0.7-1.0 m above the canopy surface.

Measuring the reflectivity of the soil surface beneath the canopy ($r_0$) was impossible because the clumped distribution of leaves prevented the solarimeter from being set in the proper position. Then, the following empirical equation was used:

$$r_0 = L \cdot r_L + (1 - L) \cdot r_D$$  

where $r_L$ and $r_D$ are the reflectivities of the completely wet and dry soil surface, respectively. $L$
is the wet portion of the soil surface, which was determined by visual observation. The values of $r_L$ and $r_D$ were measured on a plot with no crop in 1986.

All solarimeters were connected to a data logger (EKO SOLAC-III) and the output was sampled at a 30-second interval by an on-line personal computer (NEC PC-98LT). Data were averaged over 30 minutes and recorded on a floppy disk. Care was taken to keep the solarimeters level and clean.

At each test plot, three plants that showed average growth were sampled two or three times a week, then the middle size one was chosen and its leaf area (m$^2$) was measured with a leaf area meter (Hayashi, AAC-400). Leaf area index (LAI) was determined by multiplying the leaf area by the average number of plants per 1.0 m$^2$.

The coverage of a canopy ($C$) was determined by dividing the foliage width by the row spacing, assuming that there was no gap within the projected foliage area on the ground (this was not true and led to some error, as discussed later). Foliage width perpendicular to the row direction was measured two or three times a week in 1986 and 1987 by the apparatus illustrated in Fig. 2. The foliage width of a plot was determined by taking an average of ten measurements conducted on successive points along a row.

2.3. Derivation of the simplified equation

Based on the equation of Research group of evapotranspiration (1967), canopy reflectivity can be calculated by the following equation:

\[ r = r_f \cdot C + r_0 \cdot (1 - C) \]  \hspace{1cm} (5a)

\[ C = 1 - \exp(-h \cdot LAI) \] \hspace{1cm} (5b)

where $r_f$, $r_0$ and $h$ are the reflectivity of the fully-closed canopy, the reflectivity of the soil surface beneath the canopy, and a parameter, respectively.

Then, the following relationship between $h$ and $k$ (used in equation (3)) is assumed:

\[ h = k \]  \hspace{1cm} (6)

Combining equations (6), (5b), (5a), (3) and (2) gives the following simple equation:

\[ \alpha = (1 - r_f) \cdot (1 - \tau) \]  \hspace{1cm} (7)

\[ \alpha \] can be estimated easily by equation (7) because $r_f$ is constant.

The assumption expressed by equation (6) is based on the following consideration. It was assumed that $r$ is calculated by a simple proportional allocation, i.e., adding $r_f$ and $r_0$, each of which is multiplied by the fraction of area occupying the respective part (i.e., foliage and exposed soil surface) when the canopy is seen from above. Then $C$ in equation (5a) is supposed to be the coverage. Steaven et al. (1986) obtained the following relationship between $C$ and $\tau$ when the leaf inclination angle is less than 40 degrees from the horizontal:

\[ C = 1 - \tau \]  \hspace{1cm} (8)

In most cases, the leaf inclination angle of soybean is within 40 degrees from the horizontal (Kawashima, 1969, Ito and Udagawa, 1971, Hirota and Takeda, 1987). Therefore equation (8) is expected to be applicable to a soybean canopy. Substituting equation (3) into equation (8) gives $C = 1 - \exp(-k \cdot LAI)$. By comparing this with equation (5b), equation (6) was derived. Inoue et al. (1994) derived the same equation as equation (7) through the other approach.
3. Results and discussion

3.1 Transmittance

Figure 3 shows the diurnal courses of transmittance and solar radiation, which consists of four sets, i.e., (a) vs. (b), (c) vs. (d), (e) vs. (f), and (g) vs. (h). Data in each set was obtained on adjacent days with different radiation levels, i.e., clear and cloudy days. In each figure, two row directions are contrasted, so that the daily time courses of $\tau$ at similar LAI in different radiation levels and row directions can be compared. As shown in these figures, the row direction and radiation intensity hardly affected $\tau$. Therefore $\tau$ can be calculated without taking into account the row direction and radiation intensity.

In these experiments, different planting densities were provided by different plant spacings of 0.05, 0.1, 0.15, 0.2 and 0.2 m with the same row spacing of 0.6 m. Fig. 4 shows the daily mean transmittance in those plots as affected by LAI. It is apparent from this figure that the plant spacing did not affect $\tau$. Hipps (1983) also showed there was no major effect of planting densities on $\tau$ in winter wheat canopies. Regarding the effect of row spacing on $\tau$, Shibles and Weber (1966) reported that when soybeans were grown in narrow row spacings of 0.5 m or less, row spacing was of little significance. From the above discussions, it was concluded that the row direction, radiation intensity, plant spacings do not affect daily mean $\tau$ in soybean canopies, and therefore $k$ in equation (3) is independent of these factors.

Figures 5(a) shows the relationship between LAI and the daily mean transmittance to examine whether equation (3) is valid throughout the growing season with a constant value of $k$. Data from all sampling days for all plots were used. Transmittance decreased exponentially as LAI increased until LAI reached a certain value ($LAI_s$), and it did not decrease thereafter. Thus a minimum value of $\tau$ exists in practical soybean canopies. The reason $\tau$ did not decrease is because the soybeans often suffered from strong rain and wind. In the early growth stage, no damage was observed. After canopy closure, however, the canopy structure in terms of leaf distribution was disturbed. No artificial measure was taken to restore the canopy structure, therefore, the results of the experiments represent practical conditions that soybeans usually encounter. Then, equation (3) was adjusted to account for this:

\[
\tau = \exp(-k \cdot LAI) \quad (LAI < LAI_s) \tag{9a}
\]
\[
\tau = \exp(-k \cdot LAI_s) = \text{(constant)} \quad (LAI \geq LAI_s) \tag{9b}
\]

As shown in Fig. 5(a), the calculated transmittance from equations (9a, b) agreed well with the
measured transmittance. The value of \( k \) and \( LAI_8 \) were found to be 0.57 and 3.8 by an iterative procedure of minimizing the sum of the squared differences between observed and calculated \( \tau_s \).

Nakaseko (1981) suggested that varietal differences in \( k_s \) exist using the stratifying clipping method on an illumination basis. Therefore the \( k_s \) for varieties other than c.v. Enrei should be further investigated. It should be noted that the relationship between \( LAI \) and \( \tau \) was investigated by comparing the total \( LAI \) of the canopy and \( \tau \) at the ground surface on a daily basis. Lee (1990a) reported \( k \) of 0.53 for c.v. Paldalkong by the same method as the one employed in this study.

As shown in Fig. 5(b), equations (9a, b) are valid when \( LAI \) is larger than 0.1. Transmittance of a canopy with \( LAI \) of less than 0.1, however, must be known for growth analysis and prediction in the initial growth stage. Transmittance of such a sparse canopy was examined by a simple model explained in the Appendix. Comparison of the transmittances calculated by this model and by equation (9a) agreed well as shown in Fig. 6. Therefore, equations (9a, b) can be used successfully to calculate \( \tau \) as a function of \( LAI \) using a constant value of \( k \) throughout the growing season regardless of row direction, radiation intensity, or planting density.

3.2 Reflectivity and absorptivity

Figure 7 shows the dependence of \( r \) on \( LAI \) as influenced by the value of \( r_0 \) measured in 1986. Equation (4) was used to calculate \( r_0 \). The values of \( r_L \) and \( r_D \) were 0.05 and 0.11, respectively. In Fig. 7, the open circles denote the data obtained when the soil was relatively dry (0.08 < \( r_0 \) < 0.11), while the closed circles represent those obtained under relatively wet conditions (0.05 < \( r_0 \) < 0.08). Two curves of \( r \) calculated by equation (5a, b) using two values of \( r_0 \), 0.05 and 0.11 representing wet and dry soil surface respectively, are illustrated.
in Fig. 7. Apparently \( r_0 \) affects \( r \).

Equation (5a, b) is verified in Fig. 8 by comparing calculated and actual canopy reflectivity. The best fit value of \( h \) in equation (5b) was 0.50. In Fig. 8, the calculated \( r_1 \) by equation (5b) using \( k \) (extinction coefficient, = 0.57, used in equation (9a)) instead of \( h \) are shown. They are nearly equal to those calculated using \( h \), and the average difference was as small as 0.005. Therefore, \( r \) can be calculated using \( k \) instead of \( h \). Lee (1990b) also showed that \( r \) is successfully estimated by equation (5a, b) with \( k \) on a photosynthetically active radiation basis. Consequently, the practical applicability of equation (7) is justified because the only assumption necessary to derive it is that \( h \) and \( k \) are equal. The combination of equation (7) and (9a, b) is quite useful for growth analysis and prediction. The value of \( r_f \) is a constant that is considered to be specific to the variety.

Fig. 8 shows the relationship between coverage and \( LAI \) to examine the validity of equation (8), which gives the background for equation (7). The coverage almost reaches 1.0 when \( LAI \) is 4.0. The best fit curve to the data, and \((1-\tau)\) calculated using equation (9a) are illustrated by solid and broken lines, respectively. Apparently \( C \) and \((1-\tau)\) were not exactly the same. \( C \) was larger than \((1-\tau)\) by about 5% at most. Because our estimation of \( C \) was conducted based on the foliage width, there was an inevitable error caused by the gaps that can be detected in the projection of the foliage on the ground. Taking this error into account, the difference between the real \( C \) and \((1-\tau)\) is smaller than that shown in Fig. 9. The approximation of equation (8) can be used with a smaller error than 5% although precise estimation of the error cannot be made. Putting equation (8) into (7) gives

\[
\alpha = C\cdot(1-r_f) \tag{10}
\]

In most cultivation tests, growth analysis in terms of radiation utilization has not been done because frequent measurements of \( \tau \) or leaf area require much time and equipment. Our method of estimating \( C \) is so easy that frequent measurements can be done to enable the above analysis. The method, however, overestimates \( C \) as shown in Fig. 9, which may lead to some error in estimating \( \alpha \). Fig. 10 shows the comparison of \( \alpha \) calculated by the following two methods for the same canopy: one is with equation (10) using the measured \( C \) by this method, and the other is with equation (2) using the measured \( r, r_0 \) and \( \tau \). Data obtained in 1986 were used.
In the upper right part of Fig. 10, $\alpha$ calculated using $C$ were larger than those calculated using $r$, $r_o$ and $\tau$. These differences were due to lodging which was observed in the plot with a planting density of 33.3 plant/m². The lodging was caused by showers, and the angle of the stems from the vertical became larger. The foliage width increased in this case, while the real coverage had not increased as much because of the wider gaps between the leaves. Except for this case, $\alpha$ calculated by the two methods agreed well. It was concluded that $\alpha$ can be estimated successfully by equation (10) with the previously described method of measuring $C$.

4. Conclusion

This study was conducted to examine the applicability of Beer's Law to soybean growth models that calculate biomass production throughout a growing season, and to find a simple equation to estimate $\alpha$.

A simple equation (equation (7)) was derived, based on the assumption of equality between $h$ and $k$. Then the effects of row direction, radiation intensity, and planting density on $\tau$ were examined, and it was found that their effects are negligible. Next, $\tau$ was related to $LAI$ by equation (9a, b), that is proved to be applicable throughout the growing season, including the initial growth stage.

It was confirmed that $C$ can be approximated by $(1-\tau)$, and equation (10) was obtained. Equations (7) and (10) can be used for predicting and analyzing soybean growth. When $LAI$ is available, e.g., in a crop growth model, equation (7) is appropriate. When it is difficult to obtain $LAI$ or $\tau$, e.g., for a cultivation test, equation (10) should be appropriate to estimate $\alpha$.

In this paper, radiation is discussed based on total short wave radiation. However, some research has been conducted based on PAR (photosynthetically active radiation) or quantum flux. Therefore, empirical conversion among them should also be studied in the future.

Acknowledgment

The author wishes to express his gratitude to Dr. T. Sakuratani and Dr. S. Iwakiri for the encouragement and suggestions.

Appendix

As illustrated in Fig. A1, the canopy of the model consists of two leaf layers resembling a soybean canopy when it is made up of two leaf layers, i.e., layers of the primary leaves and the first leaves (cotyledons were neglected here). These leaves tend to be horizontal. Little overlap was observed within each layer. Calculation was conducted assuming that a canopy receives only the direct radiation incident perpendicular to the canopy surface.

According to Fig. A1, the fraction of overlapping leaves between the two layers ($D$) is:

$$D = \frac{T-P}{P}$$

where $T$ is the total leaf area in the canopy above a unit ground area ($U$), and $P$ is the projected foliage area on the ground.

Coverage ($C$) and $LAI$ are expressed as

$$C = \frac{P}{U}$$

$$LAI = \frac{T}{U}$$

Fig. A1. Schematic illustration of the model to estimate transmittance of a sparse canopy.
Substitution of equations (A2), (A3) into (A1) gives

$$ D = \frac{LAI}{C} - 1 $$  \hspace{1cm} (A4)

With equation (A4), $D$ was obtained readily from the tangent line of the curve shown in Fig. 9 (b) at $LAI = 0.0$, and was found to be 0.43.

From Fig. A1, the following relation to calculate transmittance ($\tau$) can be easily obtained on the assumption that there is no selectivity of wave length in light transmission through soybean leaves.

$$ \tau = \frac{1}{U} [ (U-P) + P \cdot \{ (1-D) \cdot \tau_0 + D \cdot \tau_0^2 \} ] $$  \hspace{1cm} (A5)

Where $\tau_0$ is the transmittance of a soybean leaf. $\tau_0$ was measured with a tube type pyranometer by arranging soybean leaves around it with no gap, and found to be 0.25. This value is comparable to that shown by Monteith (1965) for kale and barley.

As shown in Fig. 3(a), (b), (c) and (d), transmittance was nearly constant throughout the day, regardless of radiation intensity when $LAI$ is small. Therefore it was deduced that this model is valid for not only clear-day noon but also the wide range of radiation that a canopy would encounter.

References
R. Sameshima: Estimating the Absorptivity of Solar Radiation in Soybean Canopies


ダイズ群落の日射吸収率の推定
—生育モデルでの使用のため—

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要 約

作物群落による吸収日射量と乾物生産量の比例関係を応用した生育モデルを使用して生育予測や解析を行う場合、日々変化する群落日射吸収率（α）の正確な評価が基本となる。一般に作物はうね状に栽培され、葉群の大きさや形状は生長ともに変化する。均一な群落のある時点における光強度の垂直分布は門司・佐伯（1953）式により記述される。生育モデル内でこの式が使用可能であれば、LAIから直ちに透過率が計算できるので便利であるが、消散係数（k）が、うね方向、葉稈密度、葉群構造、天候に依存して変化する危険性がある。本論ではこの事に関する検討、および従来より少ない要素からαを評価できる簡易式の開発を目的とした。

うね幅 0.6m で栽培されたダイズ群落（品種エンレイ）の日射透過率（τ）および群落上面反射率の推移を測定した結果、生育期間を通じて一定の消散係数で門司・佐伯（1953）式が適用でき、うね方向、葉稈密度、天候は日平均透過率に影響しない事が確認された。

門司、佐伯（1953）、蒸発散研究グループ（1967）、Steavenら（1986）および岸田（1973）の式を組み合わせて次の簡易式を導出した：

\[ \alpha = (1-r_f) \cdot (1-t) \]

この式により群落下地面表面反射率と群落上面反射率の値を求める必要はない（r_f は品種毎の定数として扱える）ので吸収率の計算が容易に行え、生育モデルでの使用に有効である。更に、αを植物率から計算する次式を得た：

\[ \alpha = C \cdot (1-r_f) \]

この式と我々の用いた簡易な植物率測定法を併せて使用すると、精度良くαの推定は可能であることが確認された。この手法を一般の栽培試験に応用すれば、乾物生産量と吸収日射量の関係を基本とする生育解析が手軽に行える。

キーワード：吸収率、透過率、日射、反射率、捕捉率

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