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Reflectance Model of
a Plant Leaf

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REFLECTANCE MODEL OF A PLANT LEAF

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Abstract

A light ray, incident at about 5° to the normal, is geometrically plotted through the drawing of the cross section of a soybean leaf using Fresnel's Equations and Snell's Law. The optical mediums of the leaf considered for ray tracing are: air, cell sap, chloroplast and cell wall. The above ray is also drawn through the same leaf cross section considering cell wall and air as the only optical mediums. The values of the reflection and transmission found from ray tracing agree closely with the experimental results obtained using a Beckman DK-2A Spectroreflectometer. Similarly a light ray, incident at about 60° to the normal, is drawn through the palisade cells of a soybean leaf to illustrate the pathway of light, incident at an oblique angle, through the palisade cells.

I. Introduction

Willstätter and Stoll (W-S) in 1918, proposed a theory to explain reflectance from a leaf on the basis of critical re-

flection of visible light at spongy mesophyll cell wall - air
interfaces. According to several authors (i.e., Gates et al.[2]
and Gausman et al.[3]) their experimental results on reflectance
from leaves seem to have supported the W-S theory. Sinclair
et al.[4] gave an excellent review of the reflectance and trans-
mittance from the leaves. They critically examined the commonly
accepted W-S theory and proposed a modification, termed the
"diffuse reflectance hypothesis," which is based on diffusing
reflecting qualities of cell walls oriented at near perpendicu-
lar angles.[4] They pointed out that the microfibril structure of
the cell wall presumably induces the scattering necessary to
have diffuse reflectance. They presented experimental results
on both the reflectance and transmittance from various species
of leaves for both the visible (0.50 to 0.72 μm) and the re-
flective infrared (0.72 to 1.3 μm) wavelengths, which could not
be satisfactorily explained by the W-S theory, but which they
felt could be accounted for on the basis of their hypothesis.

Myers and Allen[5] explained the K-M (Kubelka - Munk)
scattering coefficient (of diffuse reflectance) for a typical
leaf by Fresnel reflections at normal incidence from 35 inter-
faces along the mean optical path through the leaf. Gausman
et al.[6] noted that if oblique reflections are considered, fewer
interfaces account for the results. Knipling[7] emphasized that
the air spaces within the palisade parenchyma layer of a leaf
mesophyll may be more important in scattering light than air

spaces in the spongy parenchyma layer. Allen et al.[8] have

proposed that the complex structure of the leaf can be simulated

by a pile of transparent plates with perfectly diffusing

surfaces. Birth[9] has given an excellent critical review of

existing concepts on the reflectance from a leaf. He pointed

out that the work of Sinclair[4] is enlightening in that the

diffuse character of light in the leaf is shown to start at the

initial interface. Recently, Kumar[10] has reviewed much litera-

ture pertaining to reflection from leaves.

The purpose of this investigation is to compare the

reflectance of a typical leaf found by tracing the ray of light

through the leaf with the experimentally determined reflectance

values of the same leaf. In addition, the authors would like

to investigate if considering only cell wall and air as the

optical mediums in ray tracing leads to good predictions of

experimentally determined reflectance of the leaf; and if other

optical mediums -- cell sap and chloroplasts -- should also be

included in the ray tracing for significantly better prediction

of the reflectance. Furthermore, the authors would like to

create a more realistic illustration to show the pathway of a

light ray through the leaf than shown by Willstätter and Stoll.[1]

II. <u>Cross Section of the Soybean Leaf</u>

The cross section of the soybean leaf was taken from

Sinclair's thesis.[11] This cross section had been obtained by

Sinclair by microtome cross-sectioning and a microscopic slide

was prepared using the techniques outlined by Jensen.[12] This

cross section was enlarged. An artist, well familiar with the

cross section of leaves, drew the above mentioned cross section

on a plain paper showing explicitly the cell walls, cell sap

and chloroplasts, a part of which is shown in each of Figures 1-3.

The cross section of Figure 1 was enlarged in order to do

ray tracing conveniently and accurately.

III. Reflectance From a Leaf

A. Proposed Leaf Reflectance Model. The following

assumptions are made in the reflectance model of a leaf:

1. The leaf is assumed to consist of homogeneous and

isotropic media -- cell wall, chloroplasts, cell sap and

air. This assumption is made for mathematical simplicity

so that Fresnel's Equations can be applied at each inter-

face.

2. Geometrical Optics is assumed to be valid for the media

of the leaf mentioned above. This is not quite valid for

chloroplasts (typical dimensions 5 μm to 8 μm in diameter

and about 1 μm in width[2]) where diffraction is likely to

be important.

3. The Rayleigh and Mie scattering by the leaf constituents

(of the order of wavelength of light or smaller) is ne-

glected. Gates[2] pointed out that cell dimensions of a leaf

are generally too large for scattering; however, the
chloroplasts and grana dimensions are such as to create
some scattering (i.e., grana is about 0.5 μm in length
and about 0.05 um in diameter). Scattering could also be
caused by mitochondria, ribosomes, nuclei, starch grains,
and other plastids, etc. It is very hard to take scatter-
ing into account because the dimensions, distribution and
refractive indices of these particles in the leaf cells
are extremely complex and unknown.

4. The absorption of light by the leaf media is neglected.
This is quite valid for most leaves in about 0.7 to 1.3 μm
wavelength region. Since the leaf media absorb the light
in the visible wavelengths, their indices of refraction are
complex numbers. The model presented here can also be
applied to the visible wavelengths for Fresnel's Equations
and Snell's Law are also valid for absorbing media, if one
uses the appropriate complex index of refraction.[13]
However, the ray tracing is not done in this manuscript
for the visible wavelengths since the complex indices of
refraction of the leaf constituents in these wavelengths
are not yet known. Also, the ray tracing in the visible
wavelengths becomes involved because the index of
refraction, angle of refraction, etc., are complex numbers.

5. The two dimensional cross section of a leaf (three dimensional leaf) is used for predicting the reflectance from a leaf.

B. **Basic Equations.** Fresnel's Equations, Snell's Law and boundary conditions used for determining reflection and refraction at an interface are given below.[13]

$$m_1 \sin \theta_i = m_2 \sin \theta_r \tag{1}$$

$$R_{\parallel} = \left[\frac{\left(\frac{m_2}{m_1}\right)^2 \cos \theta_i - \left[\left(\frac{m_2}{m_1}\right)^2 - \sin^2\theta_i\right]^{1/2}}{\left(\frac{m_2}{m_1}\right)^2 \cos \theta_i + \left[\left(\frac{m_2}{m_1}\right)^2 - \sin^2\theta_i\right]^{1/2}} \right]^2 I_{\parallel} \tag{2}$$

$$R_{\perp} = \left[\frac{\cos \theta_i - \left[\left(\frac{m_2}{m_1}\right)^2 - \sin^2\theta_i\right]^{1/2}}{\cos \theta_i + \left[\left(\frac{m_2}{m_1}\right)^2 - \sin^2\theta_i\right]^{1/2}} \right]^2 I_{\perp} \tag{3}$$

$$R = \frac{R_{\parallel} + R_{\perp}}{2} \tag{4}$$

$$T_{\parallel} = I_{\parallel} - R_{\parallel} \qquad (5)$$

$$T_{\perp} = I_{\perp} - R_{\perp} \qquad (6)$$

$$T = \frac{T_{\parallel} + T_{\perp}}{2} \qquad (7)$$

where

m_1 = refractive index of the first medium

m_2 = refractive index of the second medium

θ_1 = angle of incidence

θ_r = angle of refraction

$R_{\parallel}$ = reflection parallel to the plane of incidence

$R_{\perp}$ = reflection perpendicular to the plane of incidence

R = total reflection

$I_{\parallel}$ = incident intensity parallel to the plane of incidence

$I_{\perp}$ = incident intensity perpendicular to the plane of incidence.

$T_{\parallel}$ = transmission parallel to the plane of incidence

$T_{\perp}$ = transmission perpendicular to the plane of incidence

T = total transmission

C. Indices of Refraction of Leaf Constituents.

The index of refraction of the air spaces in the leaf cells is assumed to be one. The refractive index of a potato cell wall was found to be equal to 1.52 by Renck[14] in the visible

wavelengths by Index Matching Technique (i.e., The cell wall was

infiltrated with various liquids, mostly oils, having varying

refractive indices. The minimum reflectance was noted visually

with a medium having a refractive index of 1.52, which was taken

to be the best approximation to the refractive index of the pota-

to cell wall.) The potato cell wall was chosen because the homo-

geneous cell wall can be easily separated from the potato and it

does not absorb in the red wavelengths. The value of the index

of refraction of the cell wall of the soybean leaf was assumed to

be equal to 1.52 for the purpose of ray tracing, as it is likely

to be close to the refractive index of the potato cell wall. The

values of refractive indices for cell sap and chloroplasts were

taken from Charney and Brackett [15] to be equal to 1.36 and 1.42,

respectively. The values of the index of refraction of the leaf

constituents in the 0.7 µm ∿ 1.3 µm region are not available be-

cause it is quite difficult to measure the refractive indices of

the leaf constituents by the Index Matching Technique in the infrared

wavelength region as the human eye cannot see in that region.

The value of the real part of the index of refraction of water

is roughly the same in the near infrared region [16] (i.e.,

0.7 µm ∿ 1.3 µm) as in the visible wavelength region within .01.

Since water is the main constituent of the cell wall, cell sap

and chloroplasts, and since none of these absorb light strongly

in the 0.7 µm ∿ 1.3 µm region, the refractive indices of these

constituents were assumed to be the same in the 0.7 µm ∿ 1.3 µm

region as in the visible wavelength region.

D. <u>Method of Ray Tracing.</u> The four leaf constituents --
cell wall, chloroplasts, cell sap and air -- give rise to the
following eight optical interfaces in the leaf all of which
were considered in the ray tracing: 1) air to cell wall,
2) cell sap to cell wall, 3) chloroplasts to cell wall,
4) cell sap to chloroplasts, 5) chloroplasts to cell sap,
6) cell wall to chloroplasts, 7) cell wall to cell sap, and
8) cell wall to air.

In ray tracing, a ray of light of intensity $I_\parallel$ (intensity
parallel to the plane of incidence) = 1.000, and $I_\perp$ (intensity
perpendicular to the plane of incidence) = 1.000 at about 5° to
the normal was taken. The angle was taken 5° to the normal,
because in the experimental setup with the DK-2A spectroreflec-
tometer the light rays were incident at 5° to the leaf normal.
A tangent and a normal were drawn at the interface. The angle
of incidence of the ray was measured with a drafting set which
can measure angles up to an accuracy of 5 minutes. Knowing the
angle of incidence and relative index of refraction at the inter-
face, the values of θ_r, $R_\parallel$, $R_\perp$, $T_\parallel$, and $T_\perp$ were found using
equations given in Sec. 3B, and the refracted and reflected rays were
drawn. Similar procedure was followed at the subsequent inter-
faces. Each ray was continued until it ended up as reflection

or transmission from the leaf. The rays whose total intensity
became less than 0.018 were discontinued to reduce the time and
efforts required in ray tracing. The light ray passed through
a total of 253 interfaces (31 air to cell wall, 38 cell sap to
cell wall, 12 chloroplast to cell wall, 26 cell sap to chloroplast,
30 chloroplast to cell sap, 17 cell wall to chloroplast, 40 cell
wall to cell sap and 59 cell wall to air) out of which total in-
ternal reflection took place at 18 cell wall-air interfaces, two
cell wall-chloroplast interfaces, and one cell wall-cell sap
interface.

Table 1(a) shows the values of the reflected and transmitted
intensity of the ray at the interfaces. Only the rays whose
total intensity is more than 0.05 are shown in Table 1(a). The
pathway of the ray in a part of the leaf cross section, as given
by this model, is shown by solid lines in Figure 1. The numbers
along the rays represent their total intensity. For simplicity,
only the rays whose total intensity is more than 0.05 are shown
in Figure 1. Figure 2 is a more complete version of Figure 1
in that the rays whose total intensity lies between 0.018 and
0.05 are also shown in Figure 2. Figure 3 is a more complete
version of Figure 2 in that some of the rays whose total intensity
is less than 0.018 are also shown in Figure 3.

Ray tracing was also done following the same procedure as
the one mentioned above for the same original ray of light

($I_{||}$ = 1.000 and $I_{\perp}$ = 1.000) except that only the following two
interfaces were considered: 1) air to cell wall and 2) cell wall
to air. The light ray passed through a total of 144 interfaces
out of which total internal reflection took place at 13 cell wall -
air interfaces. Table 1(b) shows the values of the reflected and
transmitted intensity of the ray. Only the rays whose total
intensity is more than 0.05 are shown in Table 1(b). The path-
way of the ray considering the above two interfaces, in a part
of the leaf cross section, is shown in Figures 1 to 3 by dotted
lines. It can be seen from Figures 1 to 3 that the light ray
shown by dotted lines follows quite a different path than that
shown by solid lines.

Ray tracing was also done through the drawing of a part of
the cross-section of palisade cells of a soybean leaf, following
exactly the same procedure reported above. The light ray was
taken at an angle of about 60° to the leaf normal. The light
ray was not drawn through the complete cross section because
the only purpose of this ray tracing was to creat a realistic
illustration showing the pathway of a light ray, incident at an
oblique angle to the leaf normal, through the palisade cells.
Tables 1(c) and 1(d) show the values of the reflected and trans-
mitted intensity of the ray at the interfaces in the palisade
cells considering all the eight interfaces outlined in Section
III(D), and considering only cell wall - air and air - cell wall
interfaces, respectively. Only those rays whose intensity is
more than 0.05 are shown in Tables 1(c) and 1(d). Figure 4

shows the pathway of light through the palisade cells exactly
similar to Figure 1 (which shows the pathway of light through a
leaf cross section). Only the rays whose total intensity is more
than 0.05 are shown in Figure 4. Figure 5 is a more complete
version of Figure 4 in that some of the rays whose intensity is
less than 0.05 are also shown in Figure 5 for illustration.

It can be understood from Figures 3 and 5 that if one takes
a number of parallel rays incident on the leaf, each ray will en-
counter different geometrical internal surfaces and consequently
will be reflected and transmitted in different directions. That
is how a collimated beam of light incident on the leaf keeps on
becoming diffuse slowly as it passes through the leaf. The
greater the number of interfaces the light rays encounter in
their path, the more diffuse the rays are likely to be. The
pathway of light rays as envisioned by Willstätter and Stoll
is shown in Figure 6. It can be seen from Figure 6 that
the light rays pass through the epidermis and palisade cells
without any deviation, which is unrealistic. Furthermore,
Willstätter and Stoll did not show the reflection of light at
air - cell wall interfaces, and at cell wall - air interfaces
at angles of incidence less than the critical angle. The
authors would like to emphasize that although cell wall - air
interface causes more deviation of the ray than any other
single interface for a given angle of incidence, and is perhaps

the most important interface for contributing to the reflection
from the leaf, the other interfaces can also contribute
significantly to the reflection from a leaf   (Figure 7).

It seems that the reflection of light in the near infrared
wavelengths (0.7 $\sim$ 1.3 μm) from a typical leaf is likely to be
more diffuse than its reflection in the visible wavelengths.
This is because the near infrared light rays are likely to pass
through many more interfaces of the leaf (because of almost no
absorption of light in the near infrared wavelengths) than the
corresponding light rays of the visible wavelengths. Also, the
transmission from a leaf in the visible as well as near infrared
wavelengths is likely to be fairly diffuse because a typical
light ray has to pass through a fairly large number of inter-
faces before it is transmitted. These qualitative conclusions
support the experimental results of Breece and Holmes[17] on
healthy green soybean and corn leaves.

IV. Experimental and Ray Tracing Results

The value of reflection found by Sinclair[11] using a
Beckman DK-2A Spectroreflectometer on the same leaf, whose cross
section is shown in Figure 2, in the 0.7 $\sim$ 1.3 μm region, was
47%. Transmission = 100 - 47 = 53% (because absorption of a
leaf is almost equal to 0 in the 0.7 $\sim$ 1.3 μm wavelength region).

Ray Tracing Results

Note: The values of (reflection + transmission) found were
assumed to be 100%.

Reflection (using 8 interfaces   = 45.6%
        mentioned in sec. III D)

Transmission (using 8 interfaces = 54.4%
        mentioned in sec. III D)

Reflection (using air - cell wall   = 30.3%
    and cell wall - air interfaces)

Transmission (using air - cell wall = 69.7%
    and cell wall - air interfaces)

Experimental results of Woolley[18] on the soybean leaves

strongly support these ray tracing results. Woolley found the

reflectance of a soybean leaf in 0.7 ∿ 1.3 µm wavelength region

to be about 47 percent. But after the soybean leaf was vacuum

infiltrated with oil of refractive index 1.48, which essentially

eliminated the air to cell wall and cell wall to air interfaces

only, its reflectance dropped to about 15 percent. This

experiment clearly shows that the reflectance caused by the

discontinuities in the indices of refraction of the geometrical

surfaces (of the dimensions much larger than the wavelength of

light) is significantly more than the reflection caused due to

Rayleigh and/or Mie scattering by the particles (of the order of

wavelength of light or smaller) inside the leaf cells because

the reflectance caused by scattering should essentially remain

unchanged after the leaf is vacuum infiltrated with oils of

different refractive indices. Furthermore, it seems to support our conclusion "optical interfaces other than the cell wall to air and air to cell wall can contribute significantly to the reflection from a leaf."

V. Concluding Remarks

The preliminary conclusions, yet to be confirmed by further ray tracing, and experiments are: considering only cell wall - air and air - cell wall interfaces seems to underestimate the reflection and overestimate the transmission from a leaf. significantly in this particular case. Considering all the eight interfaces mentioned in Section III D, ray tracing seems to give results very close to the experimental results. Furthermore, considering only cell wall - air and air - cell wall interfaces is likely to give less diffuse reflectance and transmittance than that given by considering all the eight interfaces. There is some contribution to the reflection from a leaf due to Rayleigh and Mie scattering caused by the particles (of the order of the wavelength of light or smaller) in the leaf cells but the reflection caused by the leaf constituents - cell walls, cell sap, chloroplasts, and air, as given by the geometrical optics, is probably more significant than the reflection caused by scattering. Gates[2] pointed out that whatever scattering does exist is probably more of the Mie type than

the Rayleigh type because the scattering phenomena is not strongly wavelength dependent. The model presented here can also be applied to the visible wavelengths if the appropriate complex indices of refraction of the leaf constituents in the visible wavelengths are known. The authors believe that the model of a leaf presented in this article is more complete and realistic than as proposed by Willstätter and Stoll.[1] It supports the experimental results of Breece and Holmes,[17] and Woolley.[18]

For important assistance with this work we wish to thank Prof. R. M. Hoffer and Prof. M. M. Schreiber of Purdue University, and Dr. G. S. Birth of Russell Research Center, formerly with Purdue University. We also wish to thank Dr. T. R. Sinclair of Duke University, formerly with Purdue University, for letting us use his experimental results on the reflectance of the leaf.
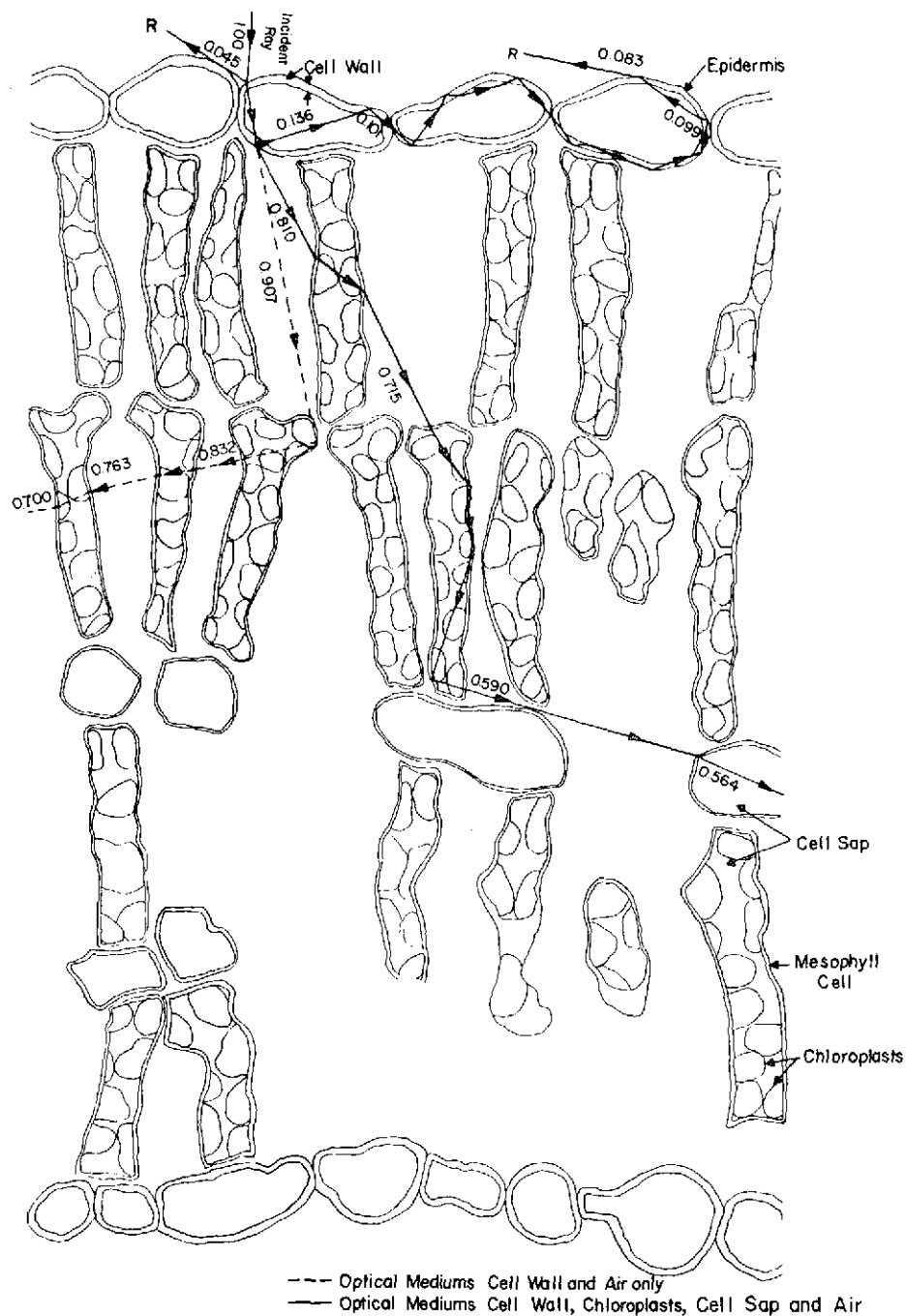
Figure 1. Pathway of light ray through the leaf cross section.
R denotes the reflected ray. Solid lines show the pathway of
light considering cell wall, chloroplasts, cell sap and air as
the optical mediums. Dotted lines show the pathway of light
considering only cell wall and air as the optical mediums. The
numbers along the rays denote their total intensity. The rays
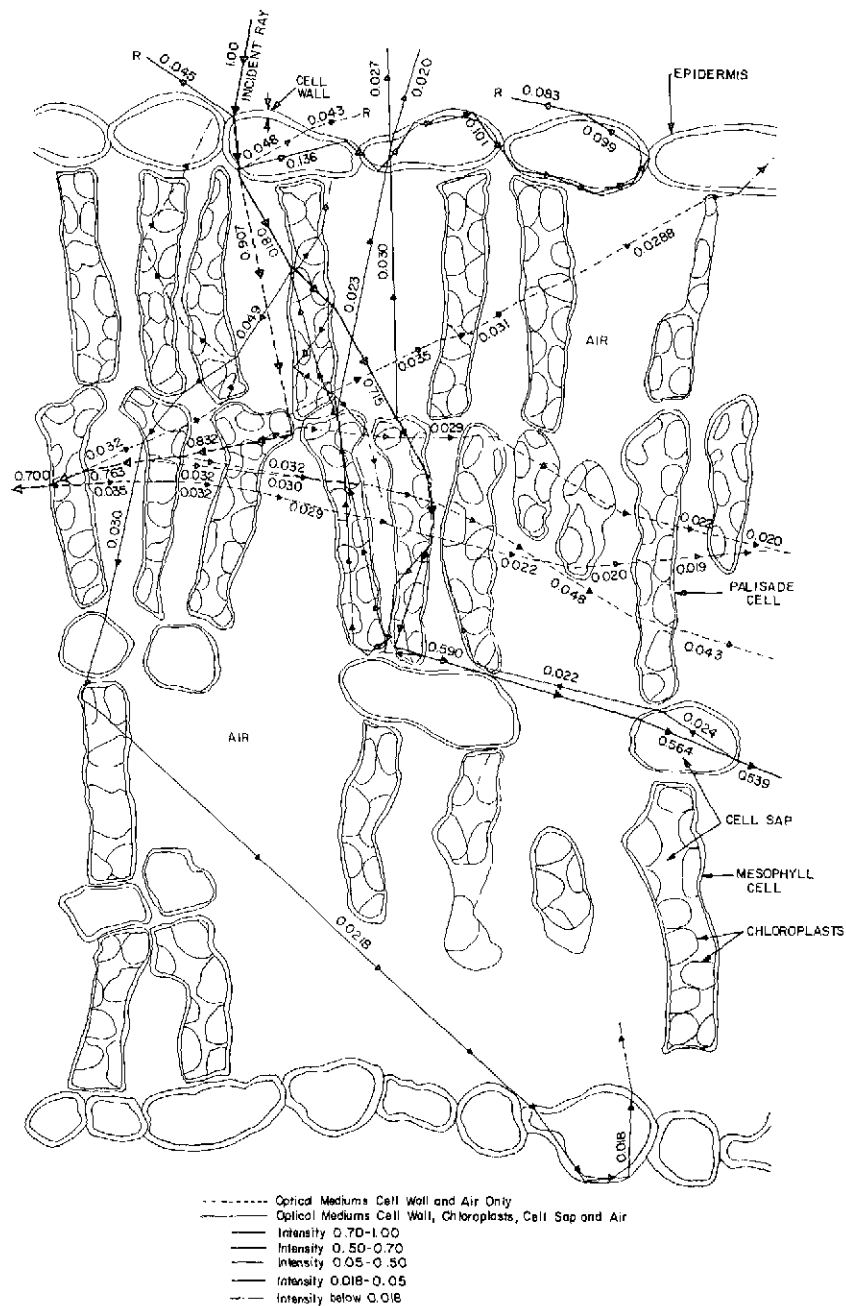whose total intensity is less than 0.05 are not shown.

Figure 2. Pathway of light ray through the leaf cross section.
R denotes the reflected ray. Solid lines show the pathway of
light considering cell wall, chloroplasts, cell sap and air as
the optical mediums. Dotted lines show the pathway of light
considering only cell wall and air as the optical mediums. The
numbers along the rays denote their total intensity. The rays
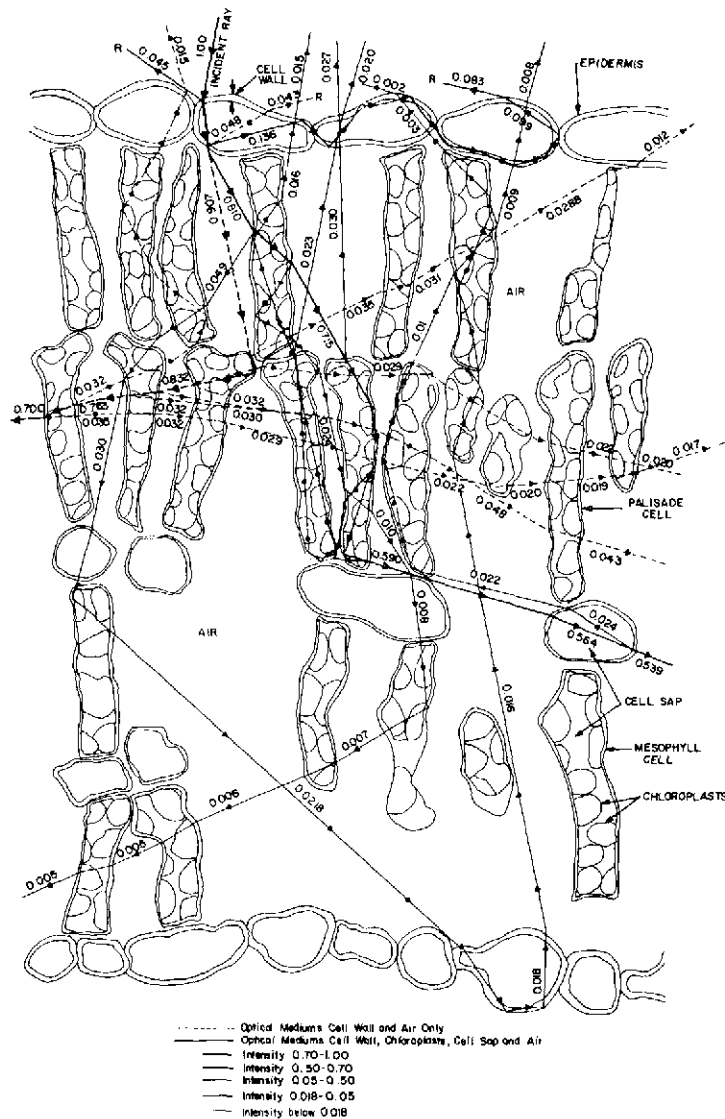whose total intensity is less than 0.018 are not shown.

Figure 3. Pathway of light ray through the leaf cross section.
R denotes the reflected ray. Solid lines show the pathway of
light considering cell wall, chloroplasts, cell sap and air as
the optical mediums. Dotted lines show the pathway of light
considering only cell wall and air as the optical mediums.
The numbers along the rays denote their total intensity. All
the rays whose total intensity is more than or equal to 0.018
are shown. Some of the rays whose total intensity is less
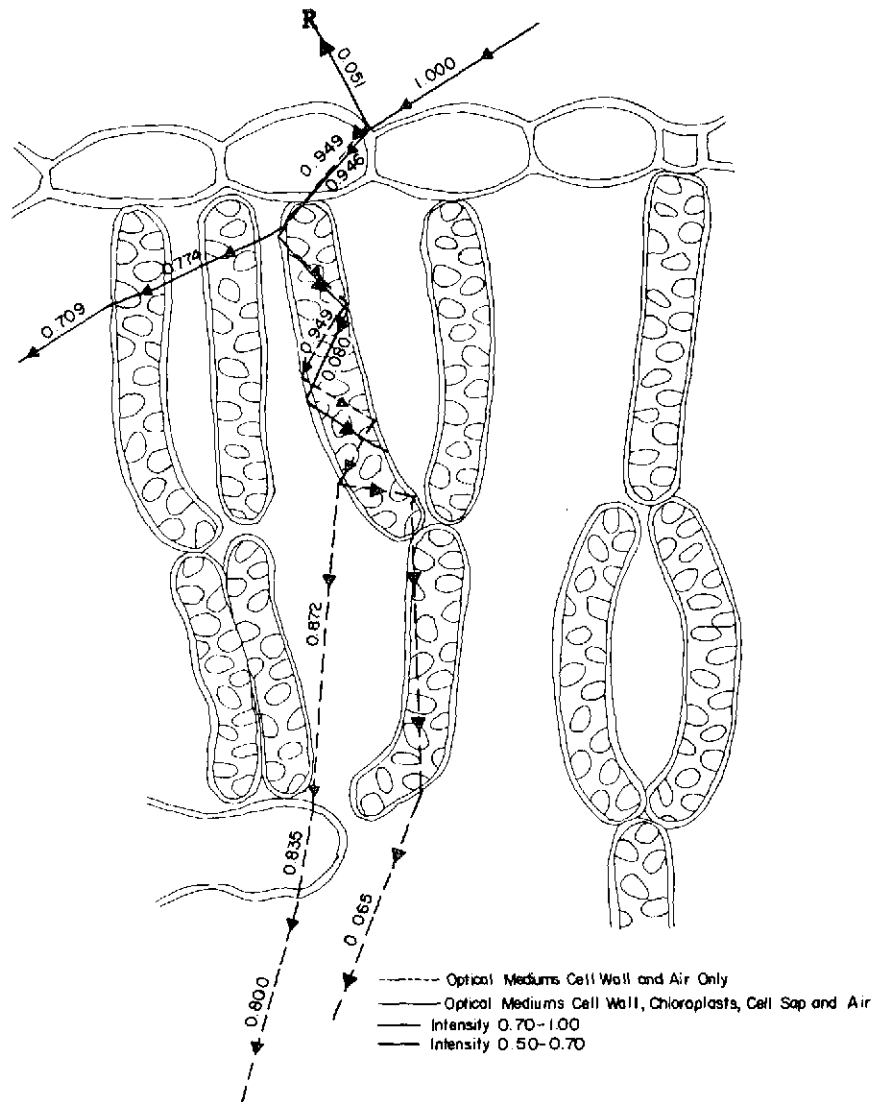than 0.018 are also shown.

Figure 4. Pathway of light through the palisade cells. R
denotes the reflected ray. Solid lines show the pathway of
light considering cell wall, chloroplasts, cell sap and air as
the optical mediums. Dotted lines show the pathway of light
considering only cell wall and air as the optical mediums. The
numbers along the rays denote their total intensity. The rays
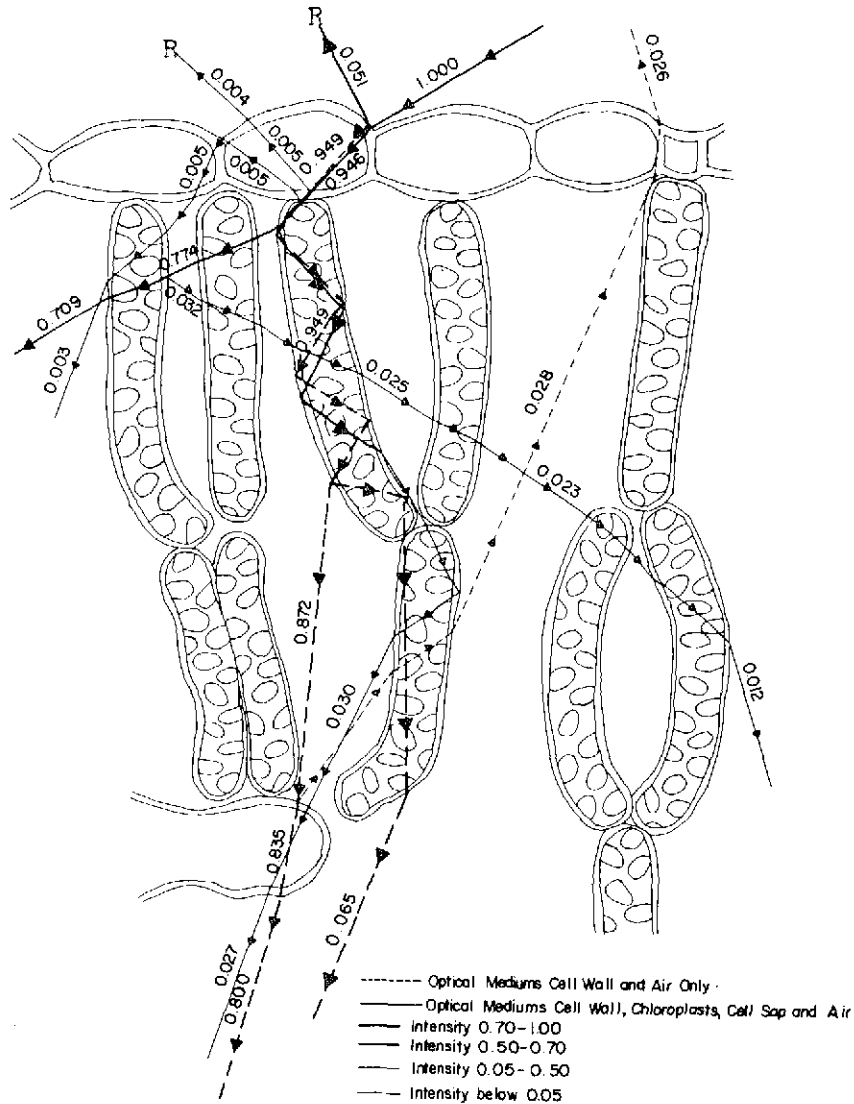whose total intensity is less than 0.05 are not shown.

Figure 5. Pathway of light ray through the palisade cells.
R denotes the reflected ray. Solid lines show the pathway
of light considering cell wall, chloroplasts, cell sap and
air as the optical mediums. Dotted lines show the pathway
of light considering only cell wall and air as the optical
mediums. The numbers along the rays denote their total in-
tensity. All the rays whose total intensity is more than
or equal to 0.05 are shown. Some of the rays whose total
intensity is less than 0.05 are also shown.
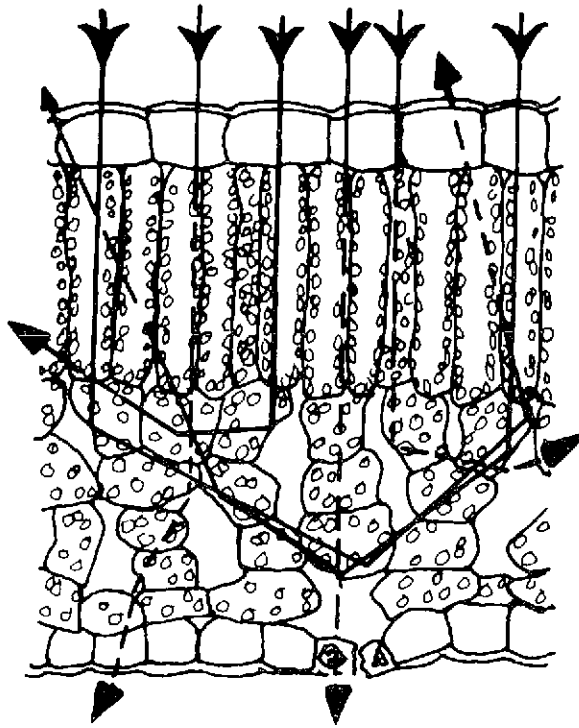
Figure 6. Pathway of light through a leaf as envisioned by
Willstatter and Stoll theory.
(Taken from Sinclair[4])
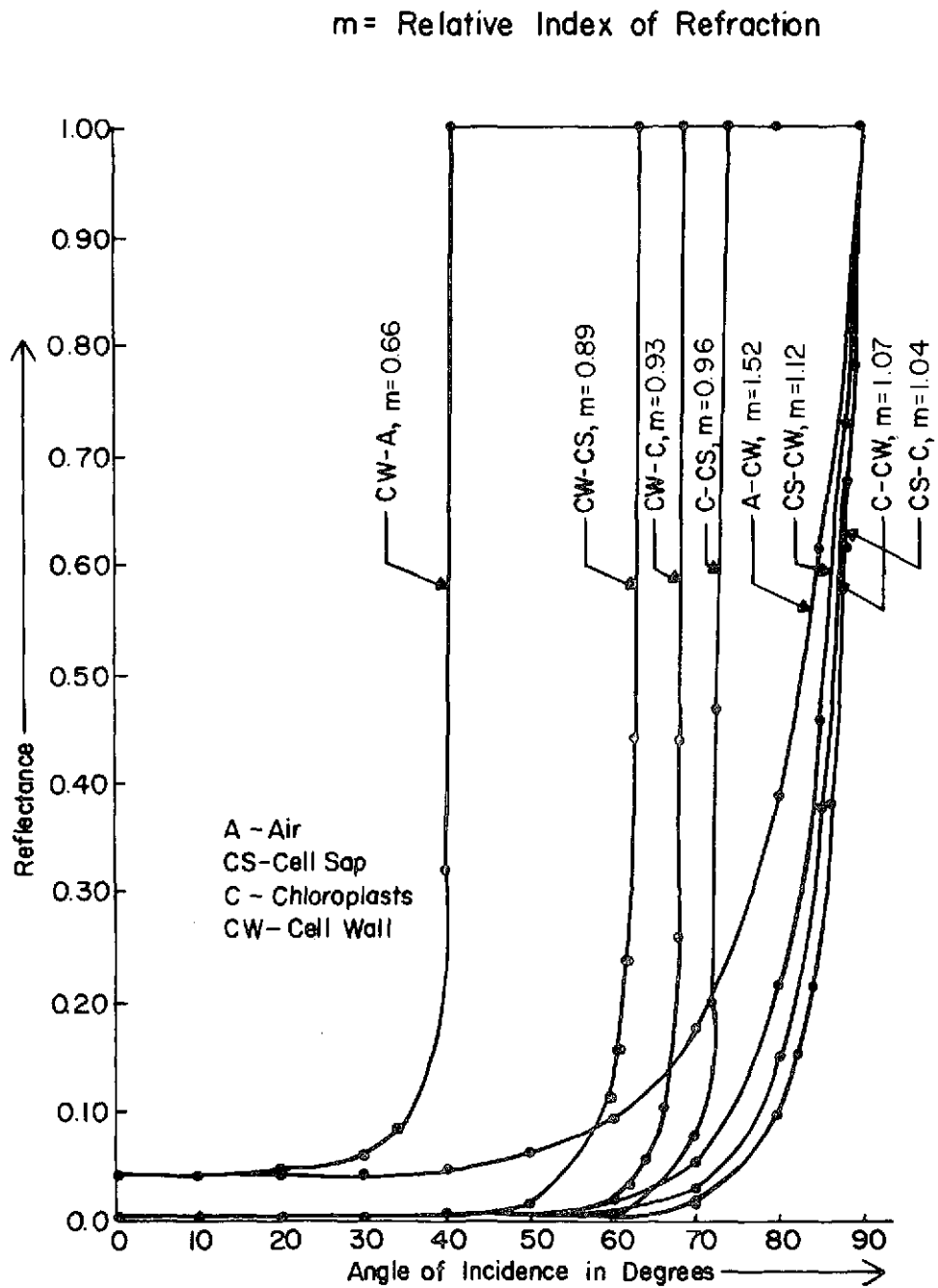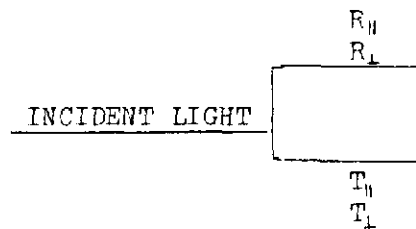
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m= Relative Index of Refraction

Figure 7. Reflectance vs. Angle of Incidence for Optical Interfaces
of a Leaf

Nomenclature for Tables 1(a) to 1(d)

Tables 1(a) to 1(d) show the intensity of the reflected ray and the transmitted ray at each interface. The total intensity of the incident ray is taken to be 1.000. The rays whose total intensity (reflected and transmitted) is less than 0.05 are not shown in the tables.

$$
\begin{array}{c}
R_{\parallel} \\
R_{\perp} \\
\hline
\text{INCIDENT LIGHT} \qquad \boxed{} \\
T_{\parallel} \\
T_{\perp}
\end{array}
$$

$R_{\parallel}$ = reflection $\parallel$ to the plane of incidence

$R_{\perp}$ = reflection $\perp$ to the plane of incidence

$T_{\parallel}$ = transmission $\parallel$ to the plane of incidence

$T_{\perp}$ = transmission $\perp$ to the plane of incidence

R = denotes that the ray has ended up as reflection

T = denotes that the ray has ended up as transmission

t = denotes total internal reflection

xx = denotes that the ray is discontinued in the table because its total intensity is less than 0.05.

--- = denotes that the value of intensity is less than 0.0005

AW   Air to Cell Wall

SW   Cell Sap to Cell Wall

CW   Chloroplasts to Cell Wall

SC   Cell Sap to Chloroplasts

CS   Chloroplasts to Cell Sap

WC   Cell Wall to Chloroplasts

WS   Cell Wall to Cell Sap

WA   Cell Wall to Air

Table 1(a). The values of the reflected and transmitted intensity of the
ray at each interface of the <u>leaf</u> cross section. The rays
whose total intensity (reflected + transmitted) is less than
0.05 are not shown in the table. The optical mediums con-
sidered are cell wall, chloroplasts, cell sap and air. The
pathway of light rays whose intensity is given in this table,
is shown by the solid lines of Figure 1.
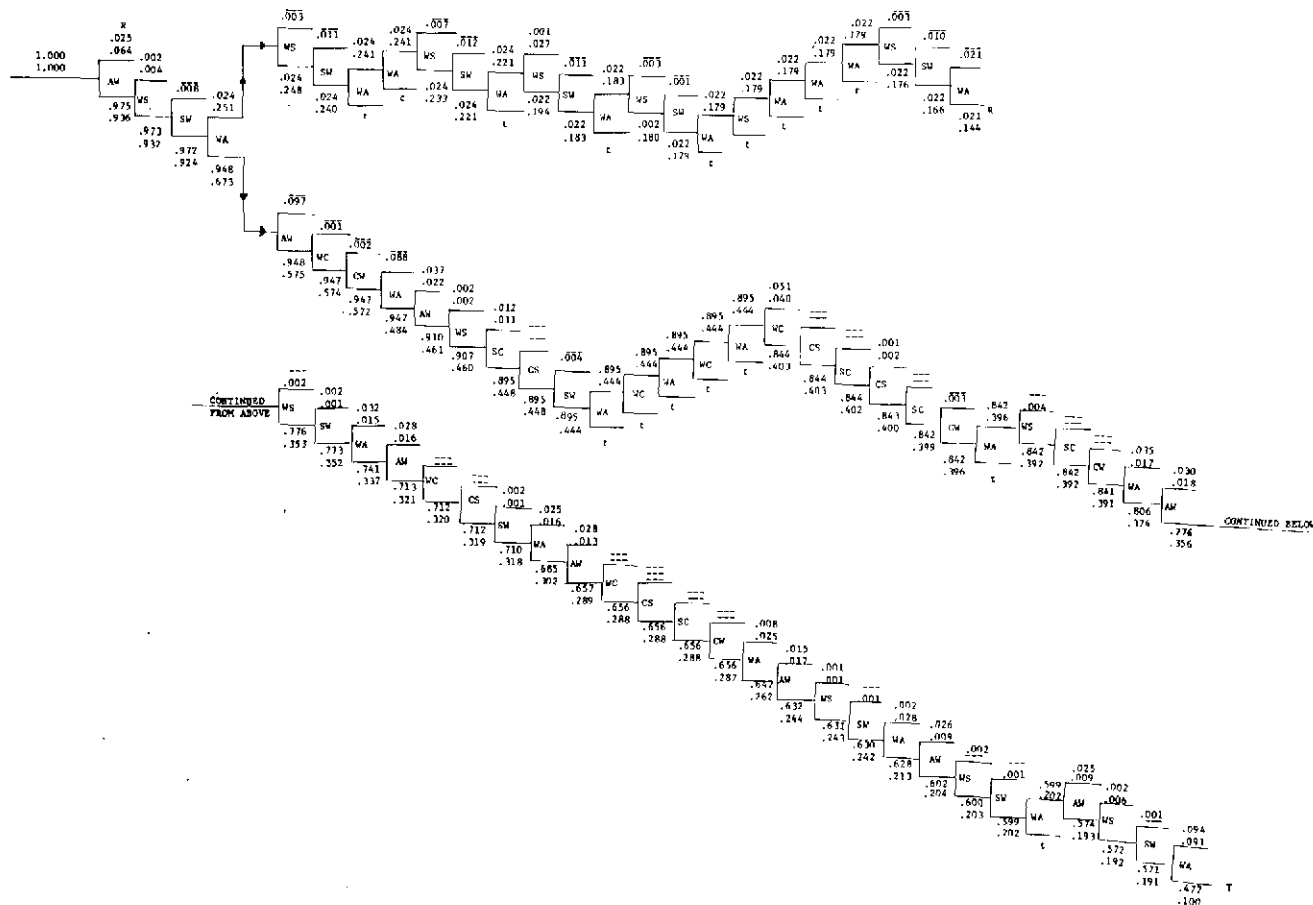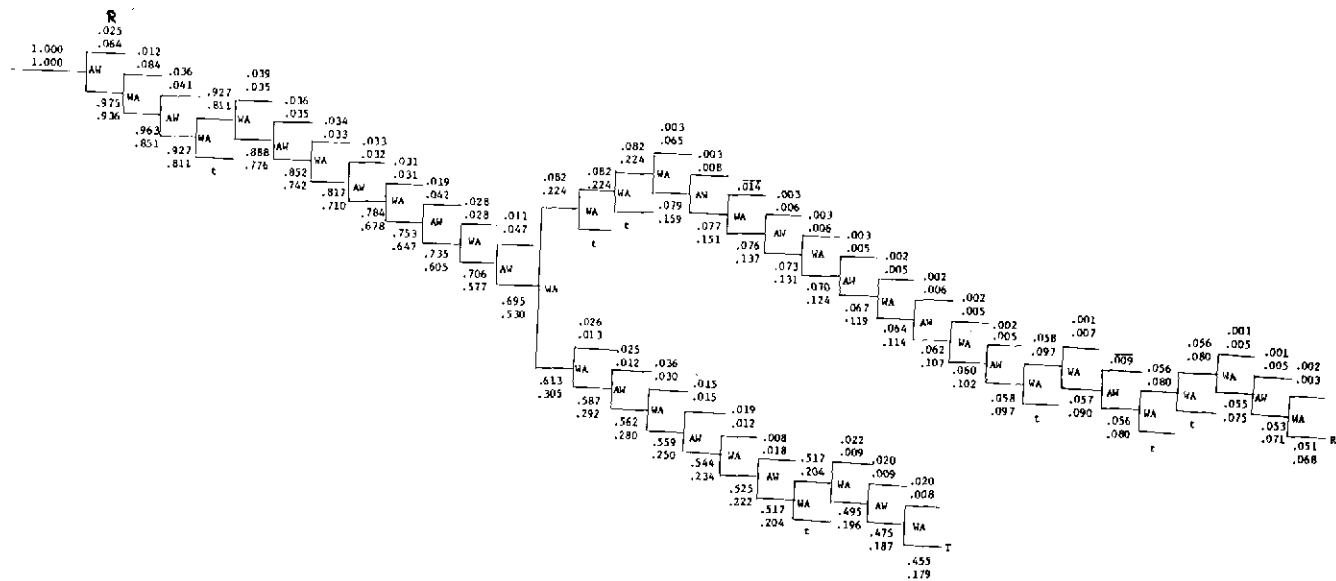
Table 1(b). The values of the reflected and transmitted intensity of
the ray at each interface of the leaf cross section. The
rays whose total intensity (reflected + transmitted) is
less than 0.05 are not shown in the table. The optical
mediums considered are cell wall and air. The pathway of
light rays whose intensity is given in this table, is
shown by dotted lines of Figure 1.

Table 1(c).   The values of the reflected and transmitted intensity of the
ray at each interface of the palisade cells. The rays whose
total intensity (reflected + transmitted) is less than 0.05
are not shown in the table. The optical mediums considered
are cell wall, chloroplasts, cell sap and air. The pathway
of light rays whose intensity is given in this table, is
shown by the solid lines of Figure 4.

Table 1(d). The values of the reflected and transmitted intensity of
the ray at each interface of the palisade cells. The rays
whose total intensity (reflected + transmitted) is less
than 0.05 are not shown in the table. The optical mediums
considered are cell wall and air. The pathway of light
rays whose intensity is given in this table, is shown by
the dotted lines of Figure 4.