A PLANT CANOPY LIGHT ABSORPTION MODEL WITH APPLICATION TO WHEAT

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ABSTRACT

A light absorption model (LAM) for vegetative plant canopies has been derived from the Suits Reflectance Model. From the LAM the absorption of light in the photosynthetically active region of the spectrum (400-700 nm) has been calculated for a Penjamo wheat crop for several situations including: (a) the percent absorption of the incident radiation by a canopy of LAI 3.1 having a 4-layer structure, (b) the percent absorption of light by the individual layers within a 4-layer canopy and by the underlying soil, (c) the percent absorption of light by each vegetative canopy layer for variable sun angle, and (d) the cumulative solar energy absorbed by the developing wheat canopy as it progresses from a single layer through its growth stages to a three layer canopy. This calculation is also presented as a function of the leaf area index and is shown to be in agreement with experimental data reported by Kanemasu on Plainsman V wheat.

I. Introduction

Remote identification of agricultural crops must be coupled with reliable yield calculations in order to provide useful tools for large scale agricultural management. The thrust of much agricultural research in recent years has been to develop crop yield models. Most yield models require determinations of plant canopy light absorption over the photosynthetically active region [1], [2], [3], of the spectrum and such determinations typically require extensive field measurements. This paper derives and discusses a canopy light absorption model (LAM) based on the canopy reflectance model developed by G. Suits [4]. The Suits reflectance model, a deterministic formulation of the Kubelka-Munk equations, relates experimentally determined plant and soil attributes to bi-directional canopy reflectance.

The LAM can be used to calculate light energy absorbed by plant canopies at any wavelength of the solar spectrum and utilizes as input parameters leaf area index, soil reflectance, sun angle, and the areas of stems, heads and leaves. In addition, the LAM calculates light energy absorbed by soil beneath the canopy. For plant canopies with layered vegetative structure, e.g., mature wheat with a layer of heads, of green leaves and of brown leaves, LAM is used to calculate the light absorption of each layer.

The authors have used the LAM to calculate the percentage of light absorbed by a wheat canopy as a function of the leaf area index throughout the growing season. These calculations show good agreement with experimental data reported recently by Kanemasu [1]. The potential of the model is further demonstrated by calculating the accumulated energy absorbed in the photosynthetically active region (PAR) by a wheat canopy from shortly after emergence until the golden stage of development. Using dry biomass measured for Penjamo wheat and the atmospheric data of Gates [10], a plant efficiency of 2.3% is calculated in agreement with the data of Bassham [12].

II. The Suits Reflectance Model.

The LAM is a natural extension of the Suits reflectance model, since the Suits model contains sufficient information about the energy fluxes within the canopy to determine absorption. Thus, one can describe both canopy reflectance and absorptance with the same set of experimental parameters. It is not the purpose of this paepr paper to detail the Suits reflectance model; such information can be found in the literature [5], [6]. However, as an indicator of the accuracy one might expect from the absorption model, a comparison between the Suits reflectance model and experimental field data is shown in Fig. 1. The solid curve shows the three-layer model values and the data points are experimental values. Shown also is the spectral reflectance of the soil. The experimental parameters were for Penjamo wheat 98 days from emergence and fully headed with a leaf area index (LAI) of 3.5. The sun polar zenith angle was 51°, and the observer was at zenith. The diffuse irradiance was 20% both at 550 and 850 nm. The model shows good agreement except in the water absorption bands. The shift in the ir shoulder is not caused by the Suits model but

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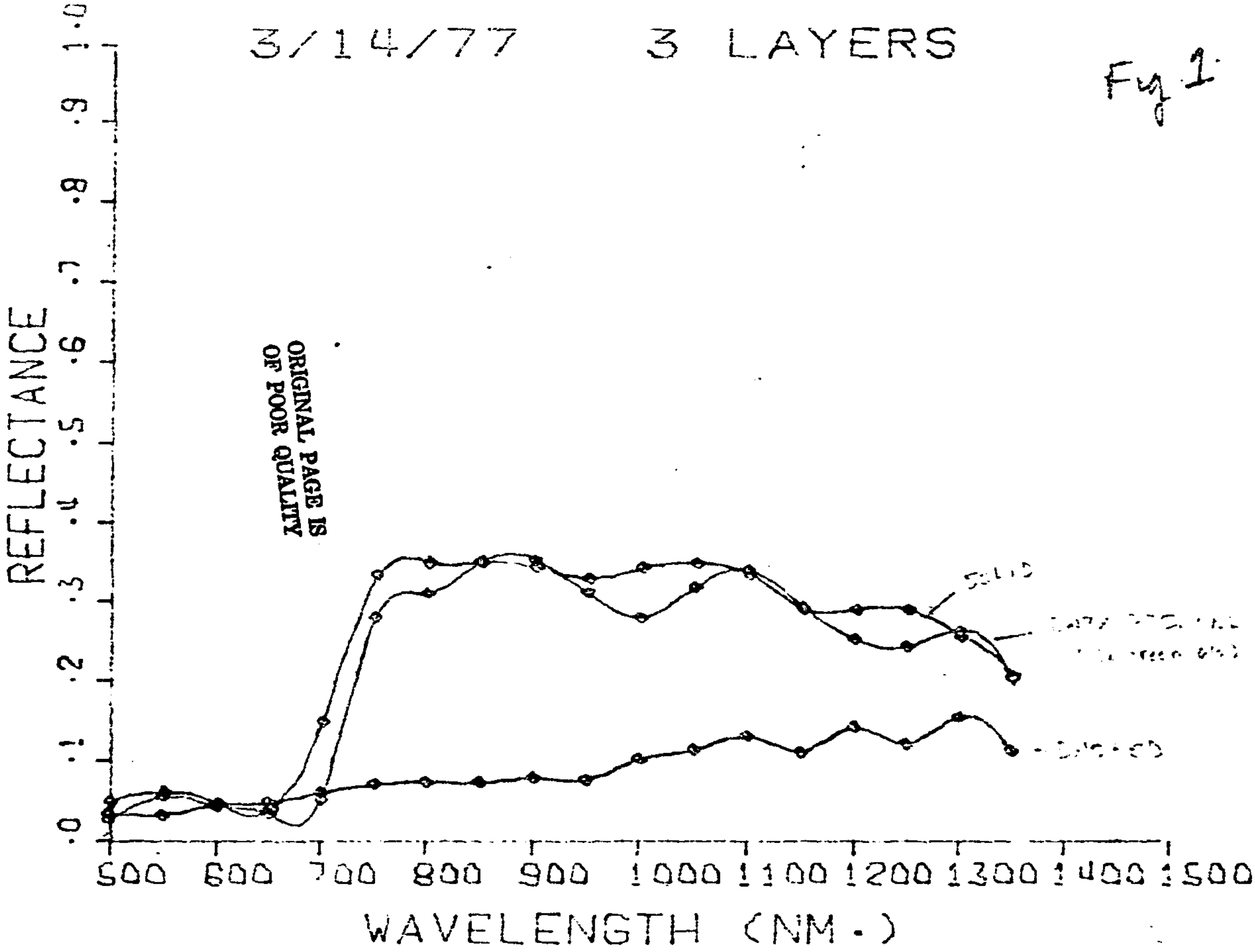
Fig 1



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is due to a wavelength calibration problem between the field radiometer, ISCO Model SR, and the laboratory radiometer, Beckman DK-2A.

III. Assumptions Used to Derive the Light Absorption Model.

In order for the reader to understand the limitations of the LAM, all assumptions used in its derivation will be listed. In many cases, the assumptions are identical with those used by Suits [4].

1. A canopy of infinite horizontal extent (no edge effects) can be divided into horizontal layers appropriate to the type of plant and its stage of growth. Within each layer more than one type of vegetative material may exist, with the different types being designated as components. For example, wheat plants in the early stages of growth can be modeled by a single layer consisting of green leaves. At the jointing stage of development, the canopy can be modeled by a single layer having two components, green leaves and stems. In the heading stage wheat can be characterized by three layers. The wheat heads are in layer 1, green leaves and stems are the components of layer 2, and the brown leaves and stems are the components of layer 3. The number of layers and components within each layer can be selected by the user for a given application.

2. The leaf azimuth angles are assumed to be distributed uniformly and the effects of sun azimuth angle are ignored in the model.

3. Hemispherical reflectance and transmittance coefficients characterize the optical properties of single leaves, stems, and heads making up a plant canopy, and these optical properties

are assumed the same for both sides of a leaf.

4. The Kubelka-Munk equations as modified by Suits describe light attenuation at a single wavelength within the horizontal layers of the plant canopy. Five coefficients are used in the LAM model for each layer; two to describe forward scattering, two to describe backward scattering, and one to describe attenuation.

5. Each leaf within the canopy is replaced by a horizontal and a vertical panel having area the same as the projected area of the leaf on a horizontal plane and two orthogonal vertical planes. By shifting projected leaf areas from horizontal to vertical, one can simulate a change in leaf slope.

6. Plant canopy specular reflectance is ignored, and the sun's position in the sky is measured by its zenith angle.

IV. The Canopy Light Absorption Model.

The plant canopy absorption model is based on a refinement by G. Suits [4] of the Kubelka-Munk (K-M) equations for the transmission and reflection of light in a diffusing medium. Suits refined the K-M equations by (1) giving deterministic formulations for the front scattering, back scattering, and attenuation coefficients, (2) assuming a horizontally layered structure for the canopy, and (3) allowing for sun angle variation.

Canopy depth x is measured from the top of the canopy with the positive direction being upward. The canopy light flux of wavelength λ at depth x in the i-th layer ($i=1,2,\ldots,N$) is subdivided into three categories: upward welling diffuse flux $E_\lambda(+d,i,x)$, downward welling diffuse flux $E_\lambda(-d,i,x)$, and specular flux $E_\lambda(s,i,x)$. The specular flux travels through the canopy until striking either a vegetative component of the canopy or the soil. If specular flux strikes a vegetative component, the energy is either absorbed or converted into upward and downward welling diffuse flux at the same wavelength. Energy conservation considerations yield

$$
\begin{aligned}
dE_\lambda(+d,i,x)/dx &= -a(i)\,E_\lambda(+d,i,x) + b(i)E_\lambda(-d,i,x) \\
&\quad +c(i)E_\lambda(s,i,x) \\
dE_\lambda(-d,i,x)/dx &= a(i)E_\lambda(-d,i,x) + b(i)E_\lambda(+d,i,x) \\
&\quad -c'(i)E_\lambda(s,i,x) \\
dE_\lambda(s,i,x)/dx &= k(i)E_\lambda(s,i,x).
\end{aligned}
\tag{1}
$$

The Suits coefficients are

$$a(i) = \sum_m a(i,m),\quad b(i) = \sum_m b(i,m),\quad c(i) = \sum_m c(i,m)$$

$$c'(i) = \sum_m c'(i,m),\quad k(i) = \sum_m k(i,m),\ \text{where}$$

$$a(i,m) = \left[\sigma_h(i,m)n(i,m)\ (1-T(i,m) + \sigma_v\ (i,m)n(i,m)\ \left\{1 - \frac{R(i,m) + T(i,m)}{2}\right\}\right], \tag{2}$$

$$b(i,m) = \left[\sigma_h(i,m)n(i,m)R(i,m) + \sigma_v(i,m)n(i,m)\ \left\{\frac{R(i,m) + T(i,m)}{2}\right\}\right], \tag{3}$$

$$c(i,m) = \left[\sigma_h(i,m)n(i,m)R(i,m) + (2/\pi)\sigma_v(i,m)n(i,m)\left(\frac{R(i,m) + T(i,m)}{2}\right)\tan\theta\right],$$

$$c'(i,m) = \left[\sigma_h(i,m)n(i,m)T(i,m) + (2/\pi)\sigma_v(i,m)n(i,m)\left(\frac{R(i,m) + T(i,m)}{2}\right)\tan\theta\right],$$

$$k(i,m) = [\sigma_h(i,m)n(i,m) + (2/\pi)\sigma_v(i,m)n(i,m)\tan\theta].$$

Where

$\sigma_h(i,m)$ is the average area of the horizontal projection of component m in layer i,

$\sigma_v(i,m)$ is the average area of the vertical projection of component m in layer i,

$n(i,m)$ is the number of projections per unit volume of components m in layer i,

$R(i,m)$ is the hemispherical reflectance of component m in layer i at wavelength λ.

and

$T(i,m)$ is the hemispherical transmittance of component m in layer i at wavelength λ.

The summations in equations (2) collect all scattering and attenuation terms from each component within a horizontal layer. Equations (3) can each be derived, but such an exercise is not within the scope of this paper.

The system of differential equations (1) requires the following initial conditions for a given wavelength λ:

$E_\lambda(s,1,0)$ = initial specular flux falling on the top surface of canopy,

$E_\lambda(-d,1,0)$ = initial downward diffuse flux from skylight falling on the top surface of the canopy.

Both initial conditions are measured experimentally by a method discussed in Section VIII. Continuity is assumed for light flux across each layer boundary, and at the soil a boundary condition is prescribed to convert a fraction ρ_s of all downward flux into upward welling diffuse flux. That is, if Z is the total depth of the canopy and ρ_s is the soil reflectance at wavelength λ, then

$$E_\lambda(+d,N,Z) = \rho_s[E_\lambda(-d,N,Z) + E_\lambda(s,N,Z)]. \tag{4}$$

A complete solution to the one layer case is derived by Allen [7] and Wendlandt and Hecht [8]. The solution to the N layer model is derived by Chance and Cantu [9], and they discuss properties of its solution.

Once the radiant flux equations (1) are solved with the appropriate initial and boundary conditions, the absorption of energy within the canopy can be calculated. This calculation characterizes the LAM. Let A(x) be the cumulative amount of energy per unit of canopy surface area absorbed from the top of the canopy to a horizontal layer of depth x in the canopy for wavelength λ. If Δx is small enough so that horizontal planes at depths x and $x+\Delta x$ both lie in layer i, then $A(x+\Delta x)-A(x)$ is the energy absorbed per unit of surface area by the canopy in the region bounded by the horizontal planes at depths x and $x+\Delta x$. The energy entering this region is

$$E_\lambda(s,i,x) + E_\lambda(-d,i,x) + E_\lambda(+d,i,x+\Delta x),$$ and the energy exiting the region is

$$E_\lambda(+d,i,x) + E_\lambda(-d,i,x+\Delta x) + E_\lambda(s,i,x+\Delta x).$$

Therefore

$$\frac{A(x+\Delta x)-A(x)}{\Delta x} = \frac{E_\lambda(+d,i,x+\Delta x) - E_\lambda(+d,i,x)}{\Delta x}$$

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$$- \frac{E_\lambda(-d,i,x+\Delta x) - E_\lambda(-d,i,x)}{\Delta x}$$

$$- \frac{E_\lambda(s,i,x+\Delta x) - E_\lambda(s,i,x)}{\Delta x},$$

so that in the limit as Δx approaches zero

$$\frac{dA(x)}{dx} = \frac{dE_\lambda(+d,i,x)}{dx} - \frac{dE_\lambda(-d,i,x)}{dx} - \frac{dE_\lambda(s,i,x)}{dx}. \qquad (5)$$

One should observe that (5) holds only when x lies within a layer; $dA(x)/dx$ fails to exist on a layer boundary.

Equation (5) is solved subject to the conditions that $A(0)=0$, and if x_i is a layer boundary, then

$$\lim_{x \to +x_i} A(x) = A(x_i).$$ Defining $A(x_i)$ in this manner insures continuity of the solution across layer boundaries. The solution to (5) is the basic equation for the LAM given by

$$A(x) = E_\lambda(+d,i,x) - E_\lambda(-d,i,x) - E_\lambda(s,i,x)$$
$$- [E_\lambda(+d,1,0) - E_\lambda(-d,1,0) - E_\lambda(s,1,0)]. \qquad (6)$$

From (6) it can be seen that the first three terms represent the net upward flux at depth x in the canopy, while the last three terms are the net upward flux at the top of the canopy.

V. Asymptotic Energy Absorption for a Canopy.

As a plant canopy grows to maturity, additional green leaves are added to increase the amount of energy absorbed from the sun. However, a point of diminishing returns is reached, so that the growth of additional green leaves contributes only a small amount to the total energy absorbed by the plant. What is the upward limit for absorption by a plant canopy when total leaf area is allowed to increase? The model presented in Section IV can be modified to answer this question by use of boundary condition (4). Equation (6) can be rewritten for a one-layer model as

$$A(x) = (1-1/\rho_s)E_\lambda(+d,i,x) - [E_\lambda(+d,1,0) - E_\lambda(-d,1,0) - E_\lambda(s,1,0)].$$

As the canopy depth increases the radiation field becomes small, so that $\lim_{x\to-\infty} E_\lambda(+d,i,x) = 0$, and

$$\lim_{x\to-\infty} A(x) = A_\infty = (E_\lambda(-d,1,0) + E_\lambda(s,1,0)) - [E_\lambda(+d,1,0)]_\infty .$$

The terms in the parentheses are the initial solar flux (downward diffuse and specular) and the term in the brackets is the limiting upward welling initial diffuse flux. If the total initial flux falling on the canopy is chosen to be 1, then a calculation gives

$$A_\infty = 1 - \left[\frac{(a+k)bc' + b^2c}{(b^2+k^2-a^2)(a+g)} + \frac{(a-k) + c'b}{a^2-k^2-b^2}\right] \quad (7)$$

where the terms in the brackets are defined by equations (3) with the layer index numbers omitted (a one layer model is assumed) and $g = \sqrt{a^2-b^2}$.

Use of equation (7) with model parameters for wheat collected by the authors indicates that a limiting absorption of 98% occurs at 650 nm, a number typical of the limiting absorption at wavelengths in the visible spectrum. A similar calculation for light at 850 nm gives a limiting absorption of 70%, typical of wavelengths in the infrared region. It is found by using the absorption model (6) with the varying canopy depth that this same canopy reaches 95% of the limiting absorption calculated from (7) with LAI in excess of 2.8 in the visible and 5.7 in the infrared. Bassham [12] states that upper limits for plant canopy absorption are estimated at 80%, a value lower than our results for wheat. However, our results show good agreement with the asymptotic experimental value of 95% in the (PAR) reported for wheat by Kanemasu[1].

VI. Results for the Light Absorption Model.

The light absorption model was applied to data collected for Penjamo wheat on April 20, 1975, at a site near Eagle Pass, Texas. The wheat was 106 days from emergence in the soft dough stage with an LAI of 3.1. A four-layer model was used with a description of the layers as follows:

(a) Layer 1 - green heads with a depth of 9 cm,

(b) Layer 2 - green leaves and stems with a depth of 20 cm,

(c) Layer 3 - green-brown senescent leaves and stems with a depth of 10 cm,

(d) Layer 4 - brown leaves and stems with a depth of 12 cm.

Figure 2a is a spectral scan of the percentage of absorbed energy per unit surface area of canopy versus the wavelength of incident sunlight assuming a vertical sun angle with 81% specular light at all wavelengths. The curve labeled total in Fig. 2 is the total percent of incident energy absorbed by the canopy, ranging from 93% in the visible spectrum to 65% in the infrared.

The other curves shown in Fig. 2a are the percentage absorption of incident sunlight by the individual layers as described in the figure caption.

Figure 2b indicates the disposition of the energy of the incident sunlight not absorbed by the canopy, i.e., energy reflected from the canopy or absorbed by the soil. The top curve is the percentage of the incoming solar energy reflected from the canopy, and the lower curve is the percentage of the incoming solar energy absorbed by the soil.

Green leaves account for over 55% of the total energy absorbed by the canopy in the PAR for a vertical sun, but this percentage decreases with increasing sun zenith angle. Figure 3a is a plot of the percent of incident solar energy absorbed per unit surface area of canopy at 650 nm in a wheat canopy of LAI 3.1 as a function of the sun zenith angle. The top curve is the total percentage of incident energy absorbed by the canopy with a range of 93-96%. The percentage of absorption by the green leaf layer decreases with increasing sun angle while the percentage of absorption by heads increases and overtakes the green leaf absorption at about a 50° sun zenith angle. This crossover is caused by the increasing optical path through the green heads that sunlight must traverse before reaching the layer of green leaves. Thus, as sun zenith angle increases, percentage absorption by the heads becomes the dominant term in the total absorption and green leaf absorption steadily decreases. In the lower curves of Fig. 4a, the percentage absorption of the green-brown leaves and the brown leaves both decrease as sun zenith angle increases. The low percentage of energy absorbed by the green-brown leaves could be a factor contributing to senescence in this layer. Leaves within this layer are not contributing sufficiently to the total energy budget of the plant. It should also be observed that while the canopy remains a very efficient absorber of energy at 650 nm for large sun zenith angles, the incident energy at this wavelength sharply decreases as a function of sun zenith angle, so that the total energy absorbed by the canopy decreases rapidly as a function of sun zenith angle.

VII. Total Energy Absorption in a Growing Season.

Using the canopy light absorption model and experimental parameters collected by the authors for wheat, total energy absorption in the PAR was calculated. Penjamo wheat, planted at the USDA experimental farm north of Weslaco, Texas, was monitored throughout its growing season, and parameters used for the canopy light absorption model were determined on a weekly basis. If $E(\lambda,\theta)$ is the spectral distribution of power falling on a square cm at the earth's surface at wavelength $\lambda(\mu m)$ for sun zenith angle θ (Joules $sec^{-1} cm^{-2} \mu m^{-1}$), $A(\lambda,\theta)$ is the percent of incident solar energy per unit area of canopy at wavelength λ (μm) with sun zenith angle θ, then the total daily energy (TDE) absorbed by the canopy (Joules per cm^2 per day) in the PAR is

$$TDE = 2 \int_{.4}^{.7} \int_{t_n}^{t_s} A(\lambda, \theta(t)) E(\lambda, \theta(t)) dt d\lambda,$$

where t_n and t_s are times for local noon and sunset respectively. The above integral is approximated by the sum

$$TDE = (2)(.3)(3600) \sum_i A(.6, \theta_i) E(.6, \theta_i), \qquad (8)$$

where the sum is evaluated over time intervals of one hour length. The sun's zenith angle was calculated on an hourly basis by use of the solar declination angle for that day with the equations of time. The function $E(.6, \theta)$ was calculated for different air masses by a fifth degree polynomial fit to data taken from Gates [10], who assumed an atmosphere with 10 millimeters concentration of precipitable water, 200 particles per cc of aerosol, and .35 centimeters of ozone.

Equation (8) was evaluated on each day that the experimental parameters for wheat were measured with results shown in Table 1. On days in which a layer of brown leaves was in the canopy, the energy absorption due to this layer was not included, since brown leaves do not contribute to photosynthetic activity.

ENERGY ABSORBED VS. TIME

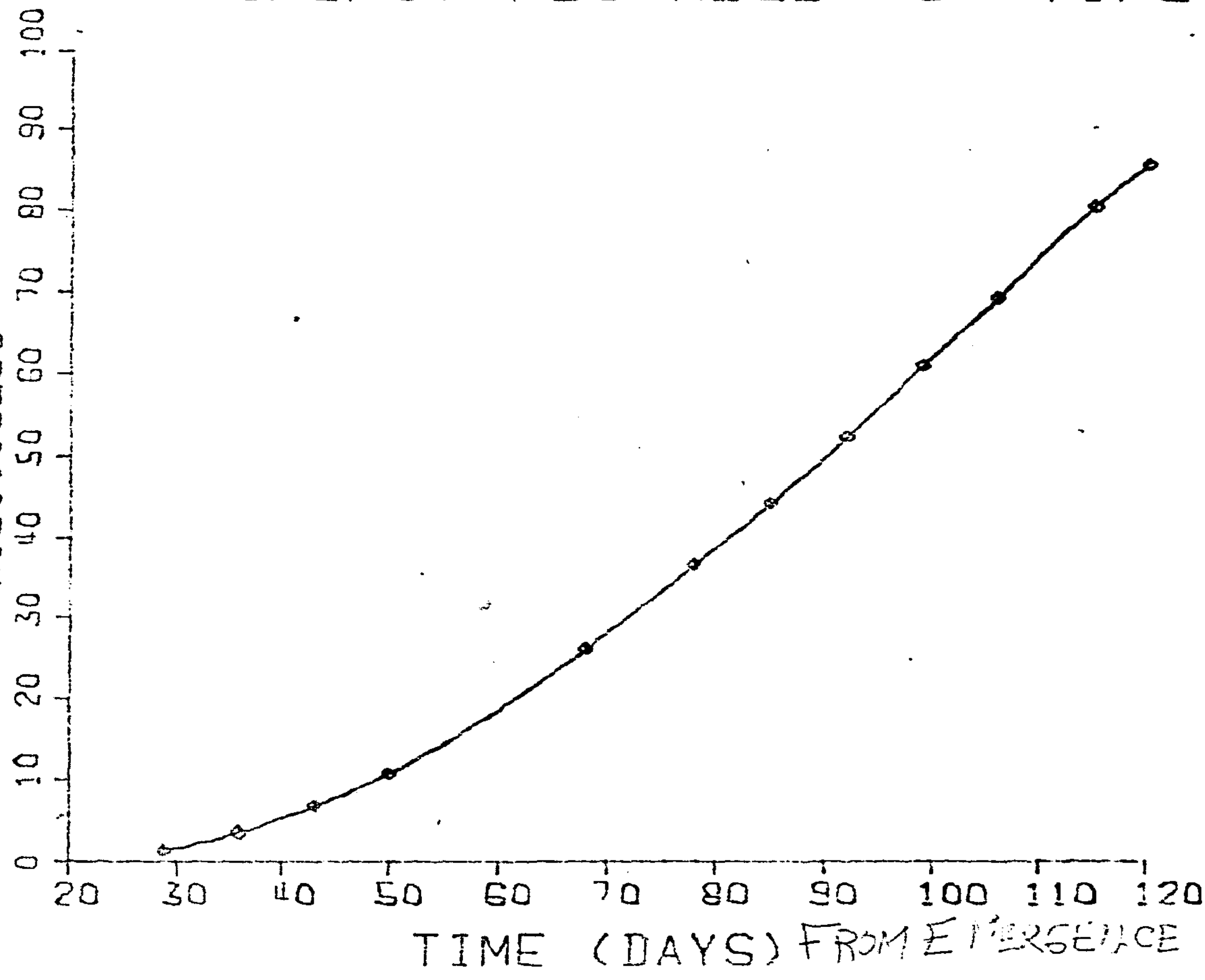

Figure 4

What portion of this total absorbed energy was used to generate biomass? Using the same atmospheric data and equation (8) with $A(\lambda,\theta) = 1$, 91.9 KJoules cm^{-2} of solar energy reached the earth's surface in the PAR at the Weslaco farm during the 120 days from emergence to the golden stage.

Measured dry biomass per unit ground area at the end of the growing season averaged .128 gm/cm^2. Assuming a conversion rate from energy to biomass of 4 KCal/gm [11], one obtains 2.14 $KJoules/cm^2$ of solar energy per unit area of canopy converted to biomass to give an efficiency of 2.3% for incident solar energy conversion to biomass in the PAR. This number compares favorably with values reported by Bassham for selected plants [12]. It is of further interest to note that, based on theoretical calculations, the plant canopy absorbs 85.4/91.9 x 100% = 93% of the total energy in the PAR arriving at the earth's surface during the growing season from planting until the onset of the golden stage. This result seems plausible when one considers that during the early stages of the wheat development with incomplete ground cover from 12-07-76 to 1-25-77 sun zenith angles are low at solar noon (50°) and the day is of short duration. But at the stages of wheat development when $LAI \geq 2.8$ (canopy absorption 95%) sun zenith angle is $\theta = 35°$ at solar noon and the days are lengthening.

VIII. Determination of the Model Parameters.

The use of this mathematical model requires a unique data base. Such a data base of the necessary parameters has been determined on a weekly basis for Penjamo and Milam spring wheats and will appear in a subsequent publication. The intent of this section is to describe the experimental techniques required to obtain the Suits-defined parameters. These parameters are sufficient to implement both the LAM and the Suits reflectance model.

The layer boundaries of a given canopy are determined visually from both the color and placement of the components. Typically, in a mature wheat crop the heads form a distinct layer, the green leaves and stems are the components in the second layer, and the brown leaves and stems make up the third layer. The layer depths are estimated with a meter stick by sighting horizontally through the canopy. The value of n(i,m), the number of elements of component m per unit volume in layer i, is found from the equation

$$n(i,m) = \frac{N(i,m)}{(X_i - X_{i-1})LW}.$$

In this equation N(i,m) is the number of elements of the component m, i.e., leaves, stems, or heads in a layer i in a sample volume of vertical thickness $X_i - X_{i-1}$, for a length L of row in which the sample is taken and width W of the row. Typically, samples were taken from 50 cm of row at several locations in a field with a row spacing W=17.7 cm.

The parameters $\sigma_h(i,m)$ and $\sigma_v(i,m)$, the horizontal and vertical projections of component m in layer i, are found from the relations

$$\sigma_h(i,m) = \frac{Area(i,m)}{N(i,m)} \cdot \cos\theta,$$

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$$\sigma_v(i,m) = \frac{Area(i,m)}{N(i,m)} \cdot \sin\theta . \tag{9}$$

The numerators are the total area of component m from layer i measured with an optical planimeter manufactured by Hyashi-Denko. The angle θ is the average slope of the component m measured from the horizontal. Equation (9) must be modified to calculate horizontal projections for heads by adding a term to account for the non-zero horizontal projection of a vertical head. Average slopes of leaves on wheat plants were found by measuring the slopes on two parts of the leaf, near the stem and at the extreme end of the leaf, and treating each as a separate measurement.

The optical properties of the wheat plant components were all determined using the Beckman DK-2A spectrophotometer at the USDA Agricultural Research Service in Weslaco, Texas. Hemispherical reflectance and transmittance were measured on samples that had been placed in plastic bags and kept over ice for transportation to the lab. The reflectance of stems and heads was measured by forming a single layer of vegetative material large enough to cover the spectrophotometer reflectance port. Optical reflectance and transmittance curves are shown in Figs. 5a and 5b for Penjamo wheat components on 3/14/77, the 98th day after emergence. The green heads, leaves and stems have qualitatively similar spectral reflectance curves. It is interesting to note that green stems generally have a greater reflectance than green leaves - an effect much like that observed when green leaves are stacked in a spectrophotometer [13]. The similarity between stem and stacked leaf reflectance is due to the fact that most wheat stems are sheathed in leaves that completely encircle the stem yielding in effect two leaf thicknesses that determine the reflectance [14].

The reflectance of brown leaves shows radically different behavior from the reflectance of green components in the canopy. The absence of chlorophyll in the brown leaves can account for the lack of strong absorption in the 550-700 nm region. The ir reflectance for brown leaves shows no absorption in the water bands, 1150 and 1450 nm, whereas the green elements show strong absorption. Figure 5b shows transmittance curves for green and brown leaves. The brown leaves are transmitting only in the ir and the green leaves have low transmittance in the visible and high transmittance in the ir.

The soil reflectance values used in the model calculations are obtained using a field spectroradiometer to measure the relative spectral reflectance of the _in situ_ soil compared to a standard reflectance panel. The sample sites were at one end of the field receiving the same irrigation and cultivation treatment as the soil between the rows.

The initial solar irradiance used in the model was partitioned by using measured values of the percent diffuse skylight and the percent specular sunlight. Measured values of diffuse light at 550 and 850 nm generally were from 15% diffuse skylight on a clear day to 100% diffuse skylight on a completely overcast day. The fraction of diffuse light is measured at a given wavelength by the ratio of the spectroradiometer reading of a standard reflectance panel shaded by a small opaque board to the unshaded standard reflectance panel reading.

The data presented in Fig. 6 show how the absorptance at 650 nm of single leaves, stems, and heads varies throughout the growing season. The absorptance was determined from measured values of reflectance and transmittance. The leaves show increasing absorptance early in the season as a result of increasing chlorophyll concentration. All components show decreasing absorptance near the end of the growing season as the chlorophyll concentration decreased. The 650 nm reflectance and transmittance of the single leaves plotted throughout the growing season show a behavior very similar to that shown for the absorptance data in Fig. 6. The leaf data suggest that reflectance and transmittance changes over much of the growing season are negligible in wheat, so that models requiring single leaf reflectance, transmittance, or absorptance data can simulate most of the growing season from a single data set.

There appears to be a slight effect in the absorptance data of Fig. 6 due to irrigation. The field was flood irrigated on day 87 and the absorptance of the leaves shows an increase of about 3% from the previous week.

The effect that canopy LAI has on the crop's ability to absorb the solar irradiance at 600 nm is shown in Fig. 7. The dashed curve ~~Curve a~~ has been calculated from Eq. (6) for solar noon with the applicable model parameters for that week. The calculations are compared with the measurements reported by Kanemasu [1] plotted in Fig. 7 as a solid curve ~~b~~. It is to be noted that the data collected by Kanemasu is for a Plainsman V wheat and the points shown on Fig. 7 are his regression fit of experimental data that show modest scatter (r^2=.87). Kanemasu's measurements of radiation in the PAR were made by using Lambda sensors. One sensor was positioned above the canopy directed upward to sense incident radiation, one sensor was pointed downward to sense radiation leaving the top of the canopy and five sensors were placed beneath the canopy to measure the radiation arriving at the soil. It was pointed out to the authors [14] that the Kanemasu measurements are simply the terms of Eq. (6).

The data of Fig. 7 used the LAM only at 600 nm to approximate canopy absorption in the PAR, since the incident solar energy in the PAR is equivalent to that incident energy produced by sunlight at 575 nm [12]. It is clear from the agreement between the LAM results and experimental data that model calculations can be used for many applications instead of direct measurements.

IX. Discussion.

The reflectance model developed by Suits contains not only information about light exiting the top of a plant canopy but also light flux relations within the canopy. Knowing the plant structural and optical parameters allows one to calculate the percent absorptance of the canopy and its component parts. Knowing further the solar energy distribution at the surface of the canopy, one can calculate the light energy absorbed either in the canopy or by the soil beneath the canopy. The versatility of the model allows sun angle variations for studying diurnal effects or seasonal effects from sun declination. Soil temperatures effects can be studied throughout the growing season by using the soil energy absorption calculations of this model. Absorption in the PAR of specific parts of a plant, such as flag leaf, head, stem, etc., can be determined from this model as shown in Fig. 2.

The canopy light absorption model can be used to establish an asymptotic upper bound for absorption at 98% by wheat canopies in the PAR and 70% in the ir region of the spectrum. Further, wheat canopy light absorption is within 95% of these asymptotes for LAI's exceeding 2.8 in the PAR and 5.3 in the ir.

X. Conclusions.

1. A light absorption model for plant canopies has been derived from the Suits reflectance model for vegetative canopies providing an accurate calculation technique having many variables that can be adjusted to represent environmental or plant conditions.

2. Wheat canopy light absorption increases as a function of crop LAI approaching an asymptotic absorption of 98% in the PAR and 70% in the ir. In practice, however, the model predicts wheat canopy absorption within 5% of its asymptotic values for LAI in excess of 2.8 in the PAR and 5.7 in the ir. These model predictions for percentage light absorption as a function of LAI show agreement with direct experimental data collected by Kanemasu [1].

3. For wheat canopies with moderate LAI (≈3) having green, immature heads, the percentage of light absorption by the canopy is only slightly affected by the variation in sun zenith angle. As sun zenith angles become progressively larger, the percentage of light absorbed by the green leaves decreases, while on the other hand, the percentage of light absorption by the green heads increases. Light absorption by the layer of green-brown leaves remains uniformly low for all sun zenith angles, suggesting a possible reason for the senescence of these leaves.

4. Cumulative light absorption in the PAR can be simulated with the light absorption model and solar energy distribution data. Such an analysis suggests that from emergence to the golden stage the vegetation absorbs 85.4 KJoules of energy per cm^2 of horizontal canopy surface area in the PAR. Combined with the measured biomass of Penjamo wheat, this gives a 2.3% efficiency of conversion to biomass in the PAR in agreement with published data.

5. Plant parameters used in the absorption model are both physical and optical. The physical plant parameters allow canopy component slope, LAI, and vertical extent to be varied. The optical reflectance and transmittance showed little variation over the growing season, hence require only 3 or 4 samplings.

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14. Communication with Dr. C. L. Wiegand.

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Figure Captions

Fig. 1. A comparison of the Suits 3 layer reflectance model with experimental data for Penjamo wheat in the soft dough stage 98 days from emergence with an LAI of 3.5. Soil reflectance is shown for comparison.

Fig. 2 (a). LAM calculations for a 4 layer Penjamo wheat canopy of LAI 3.1 as a function of the wavelength of incident light. The absorption of each canopy layer is shown as well as the total canopy absorption.

(b). LAM calculations for percentage absorption of light by the underlying soil beneath the 4 layer canopy. Also shown is the percentage of incident light exiting the top surface of the canopy.

Fig. 3 (a). The percent absorbed energy of 650 nm incident light calculated by the LAM for a four layer Penjamo wheat canopy as a function of the sun zenith angle. The absorption of each canopy layer is shown as well as the total canopy absorption.

(b). The underlying soil absorption and exiting upward flux calculations are shown for variable sun zenith angle.

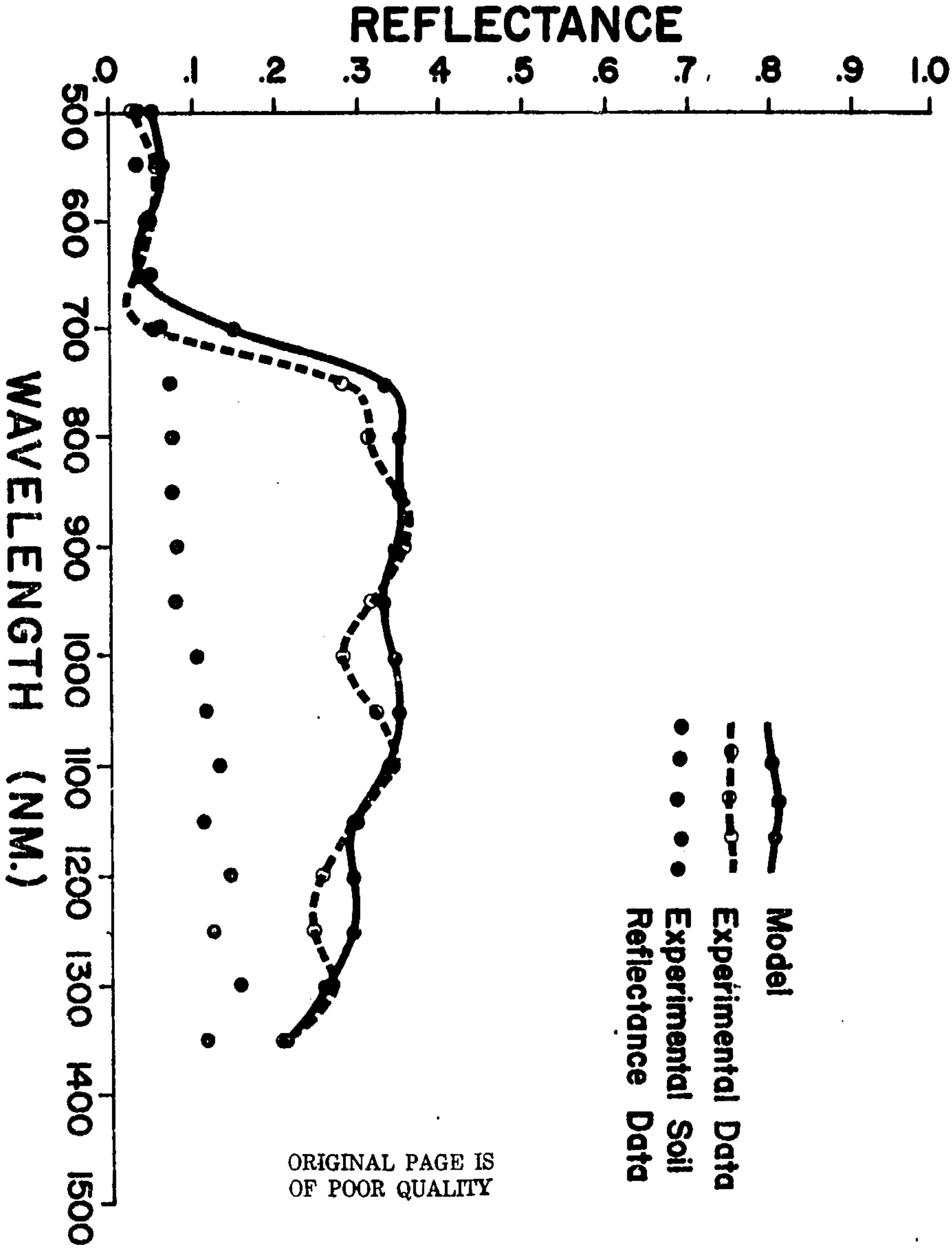
Fig. 4. Cumulative energy absorbed in the PAR by a wheat canopy throughout the growing season.

Fig. 5 (a). The reflectance of vegetative components in a well developed Penjamo wheat canopy measured 98 days from emergence.

(b). The transmittance of green and brown leaves taken from the same Penjamo wheat canopy.

Fig. 6. The absorptance of vegetative components throughout most of the growing season.

Fig. 7. A comparison of LAM absorption calculations with the experimental results of Kanemasu for varying LAI.



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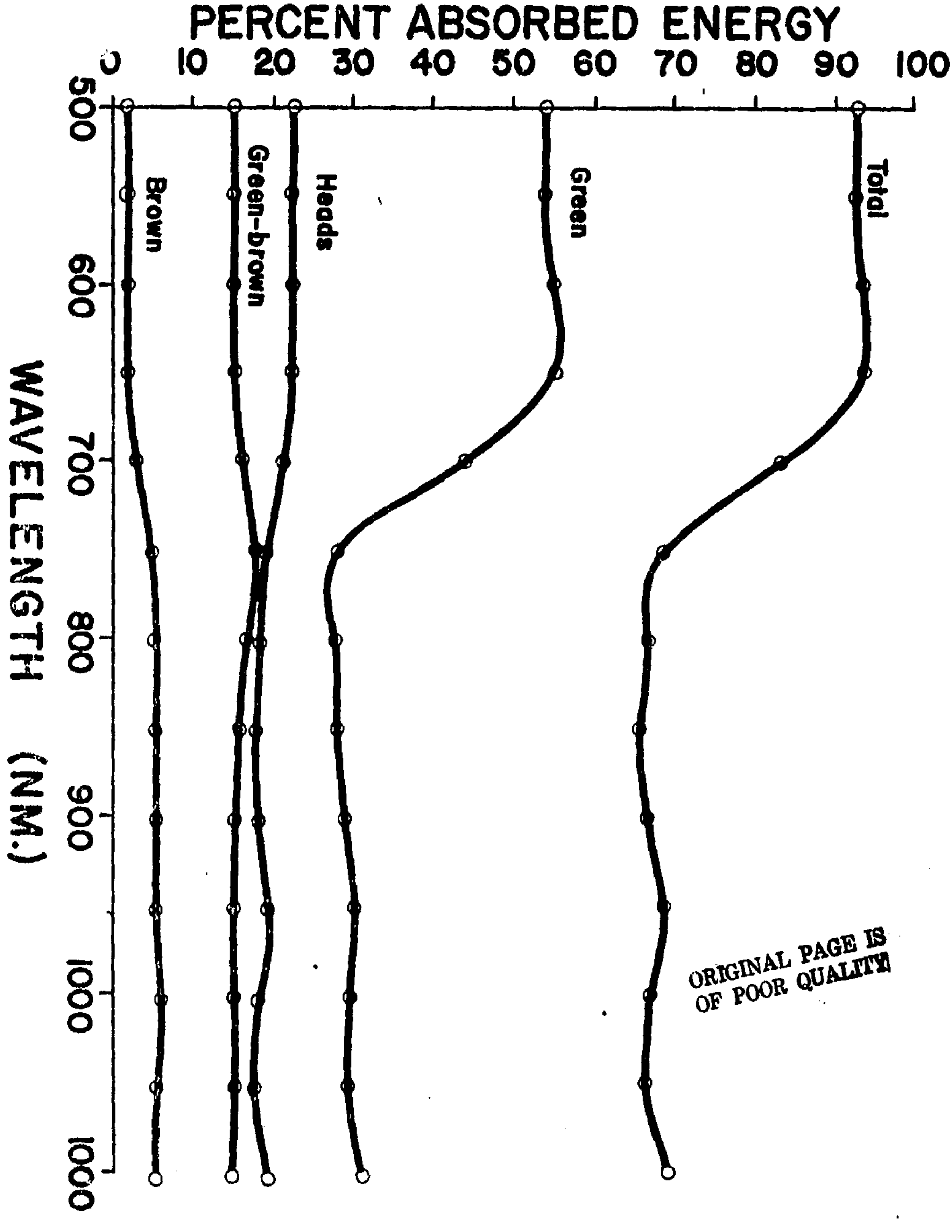

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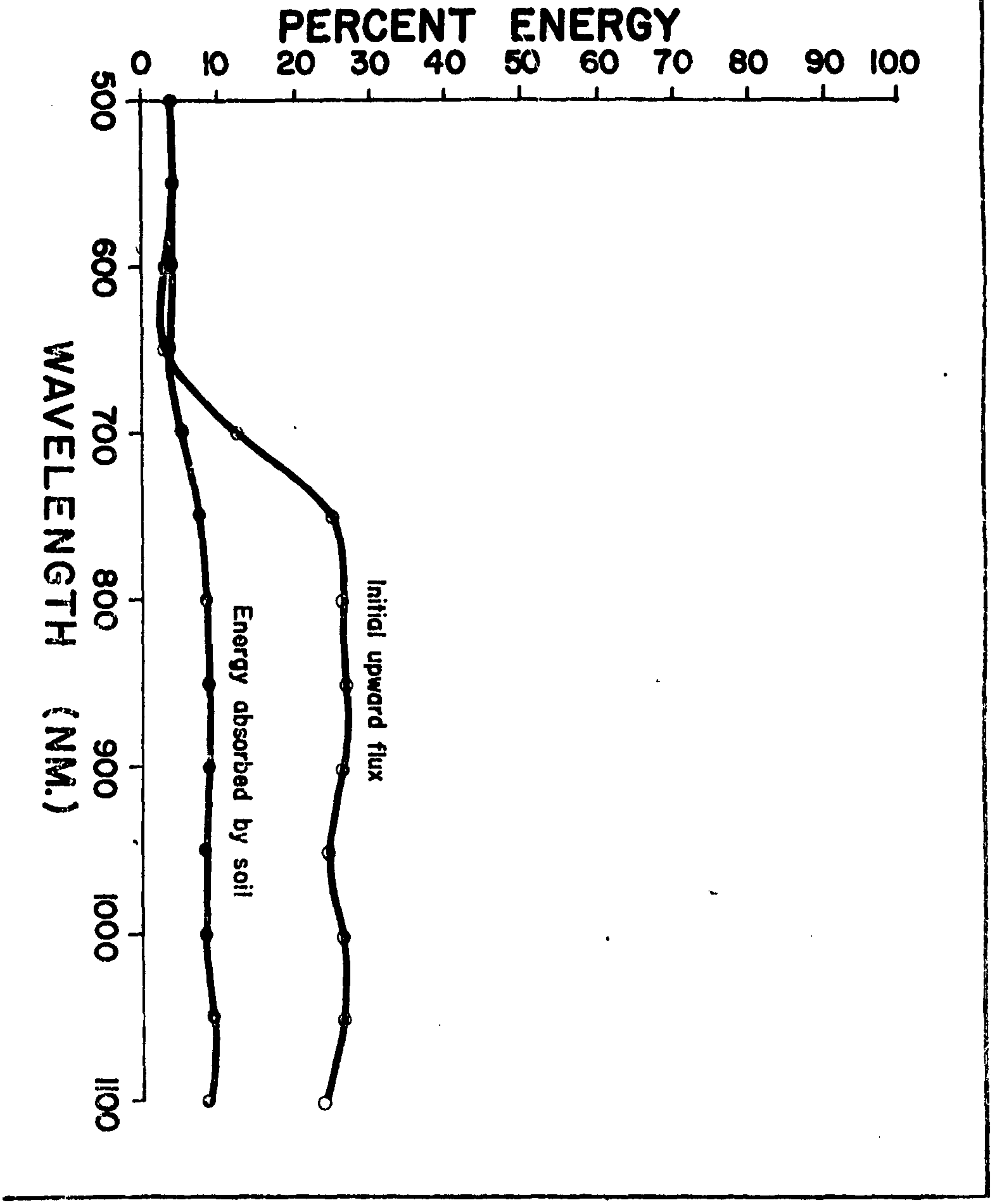
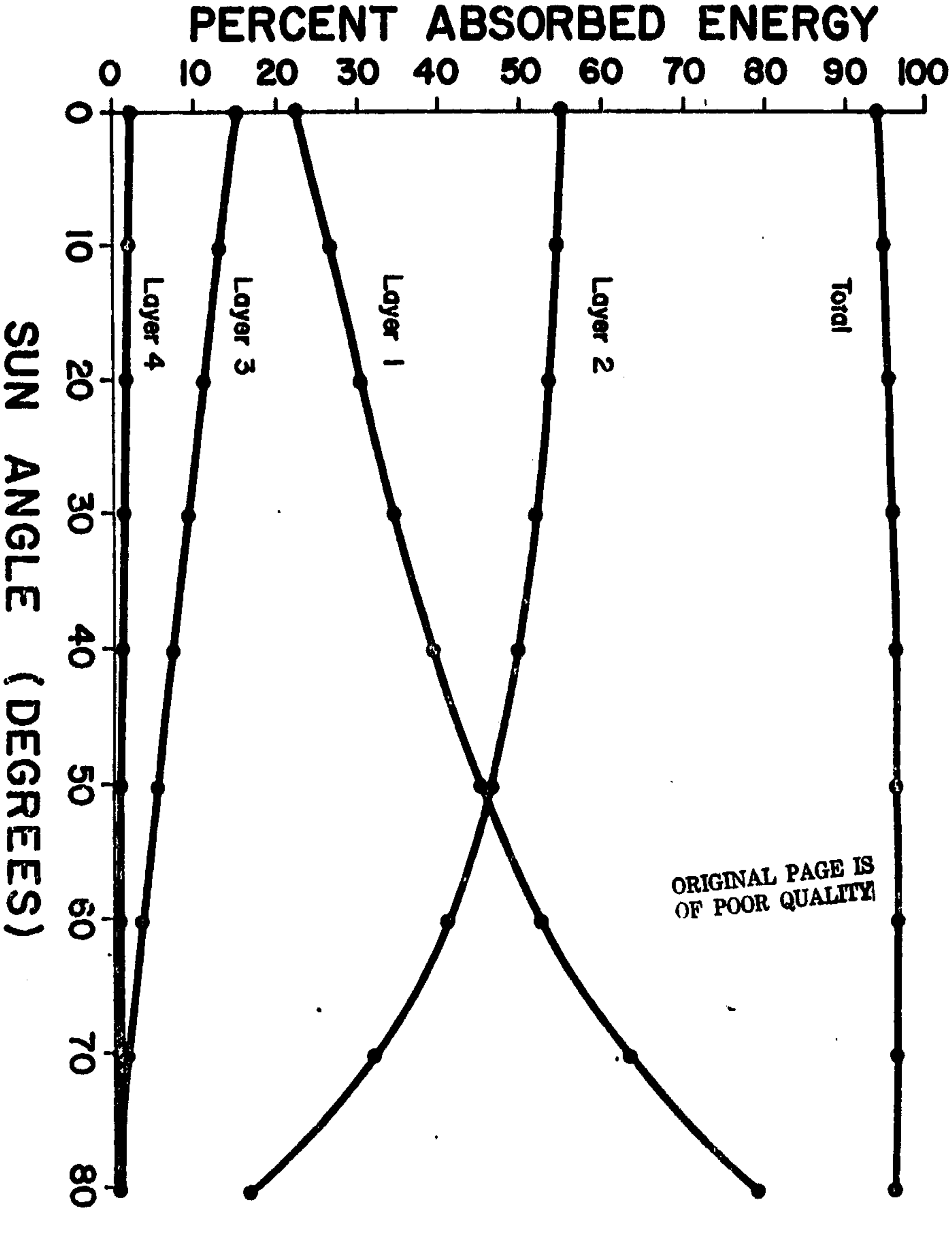


Fig. 2 (b). LAM calculations for percentage absorption of light by the underlying soil beneath the 4 layer canopy. Also shown is the percentage of incident light exiting the top surface of the canopy



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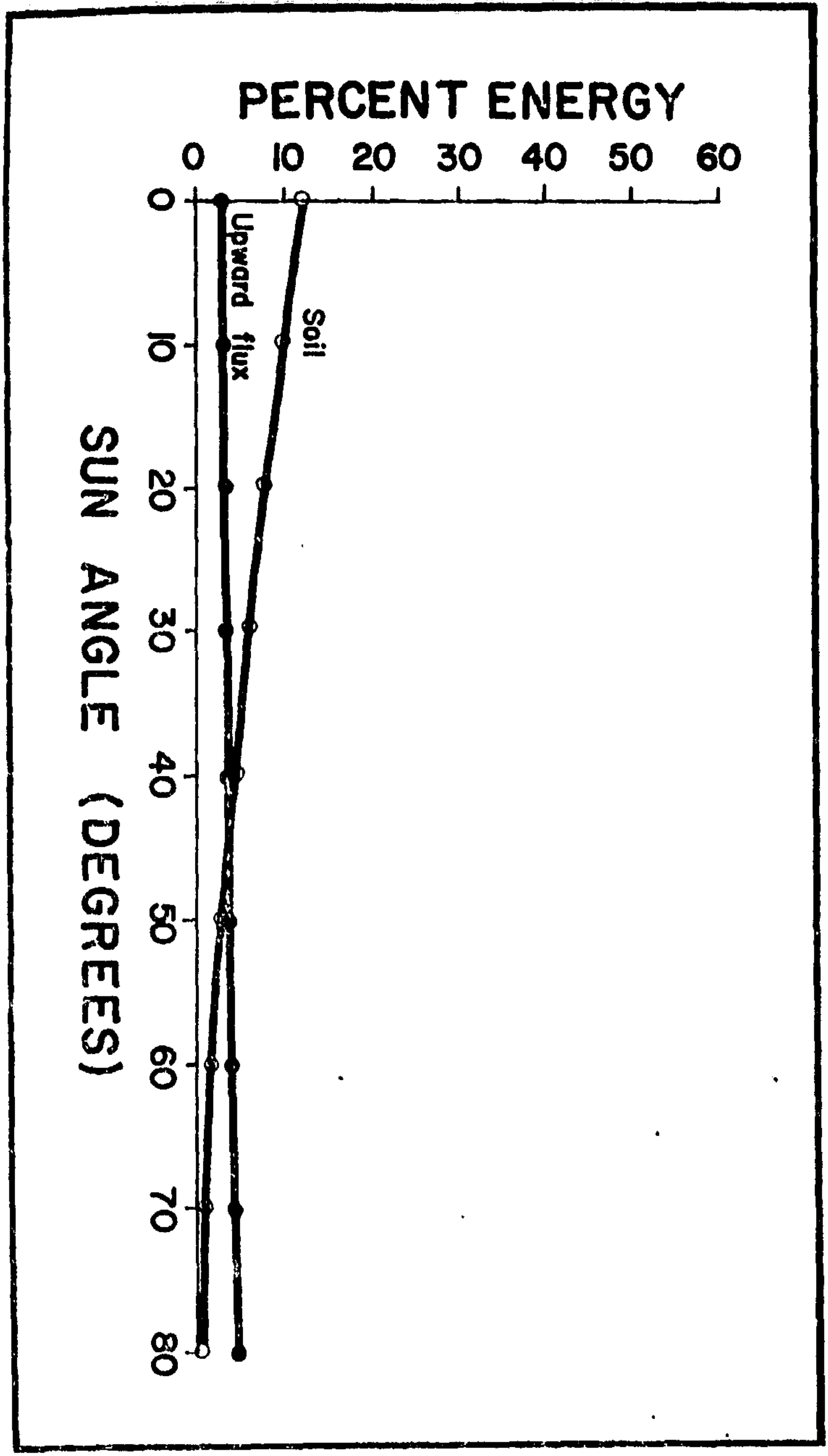

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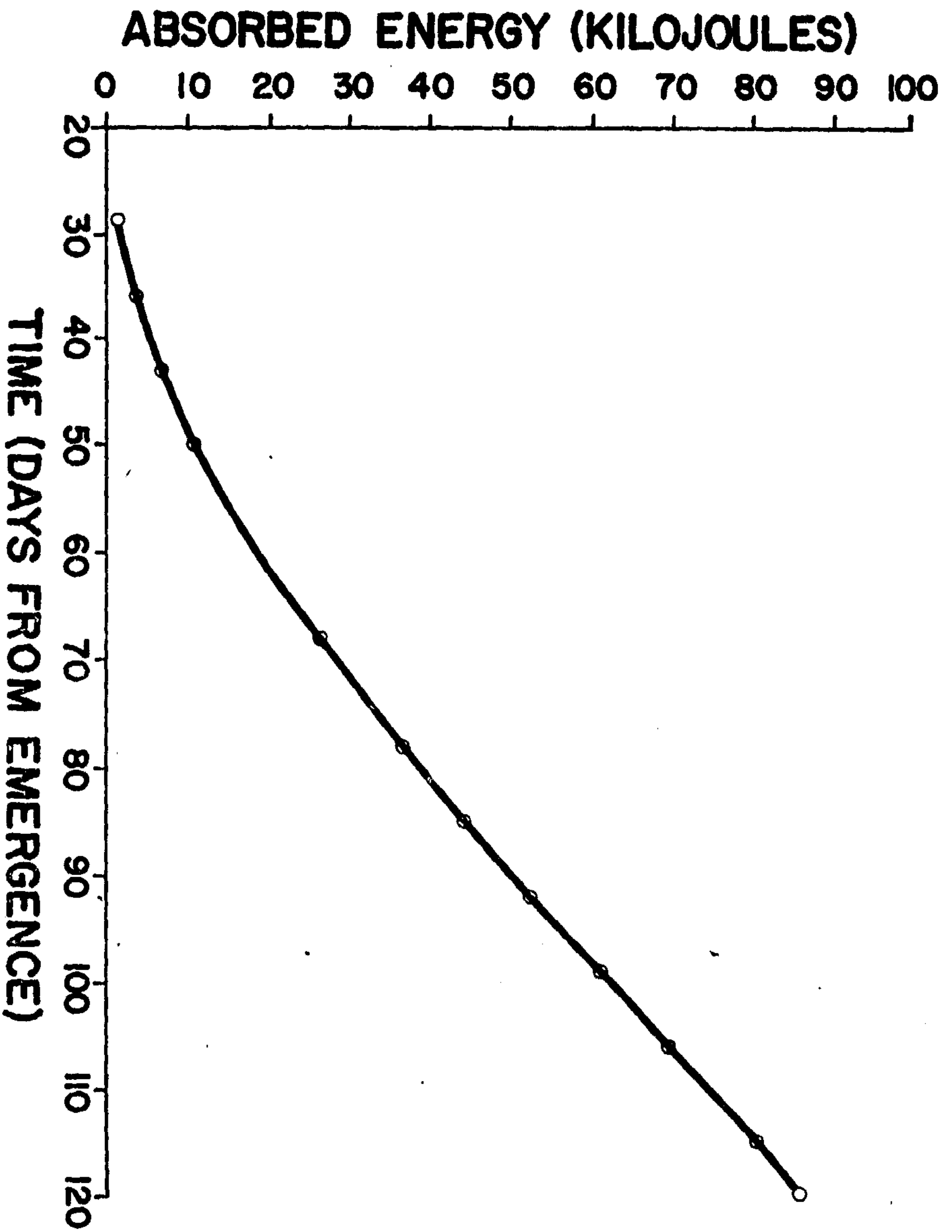

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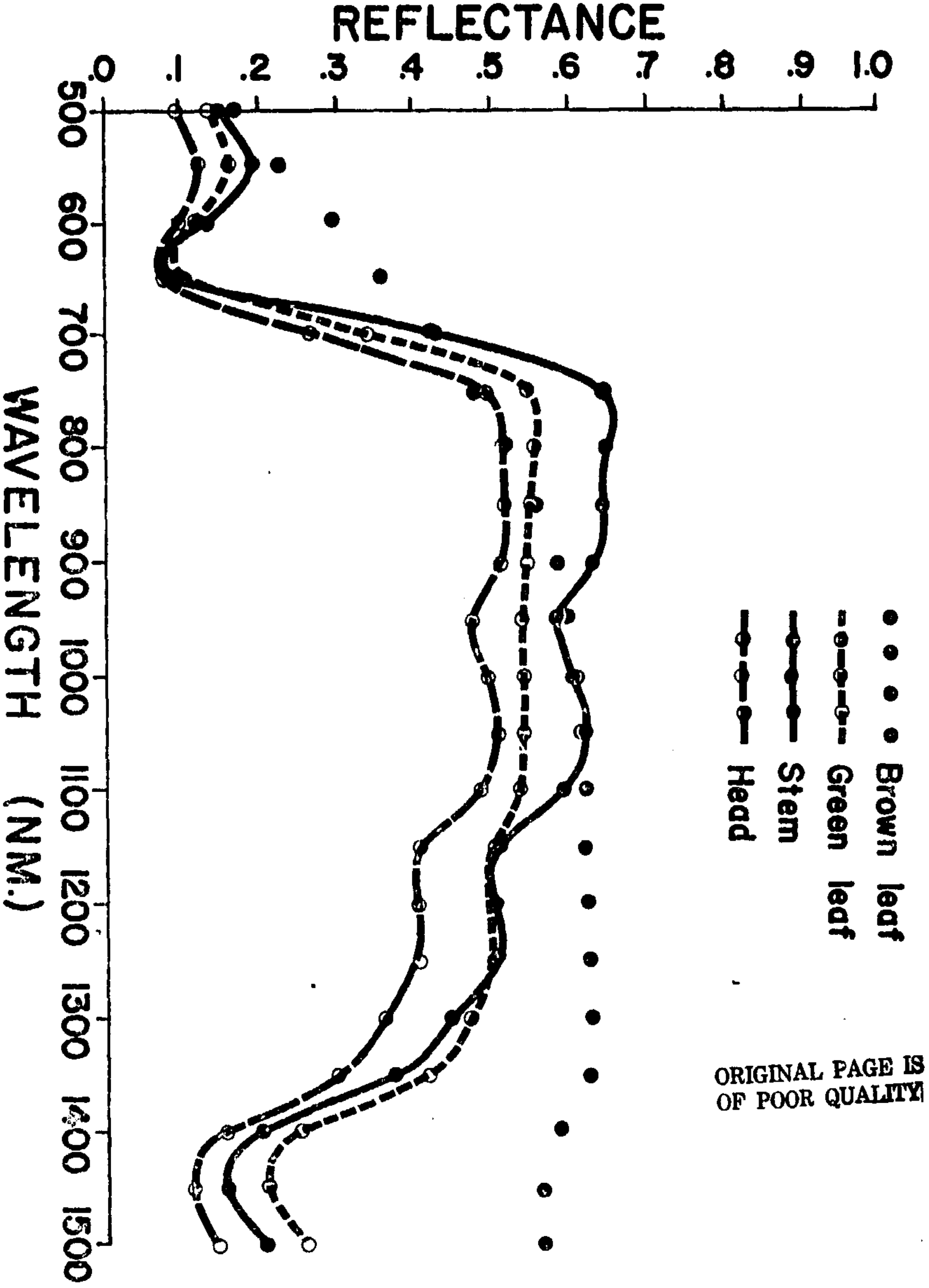

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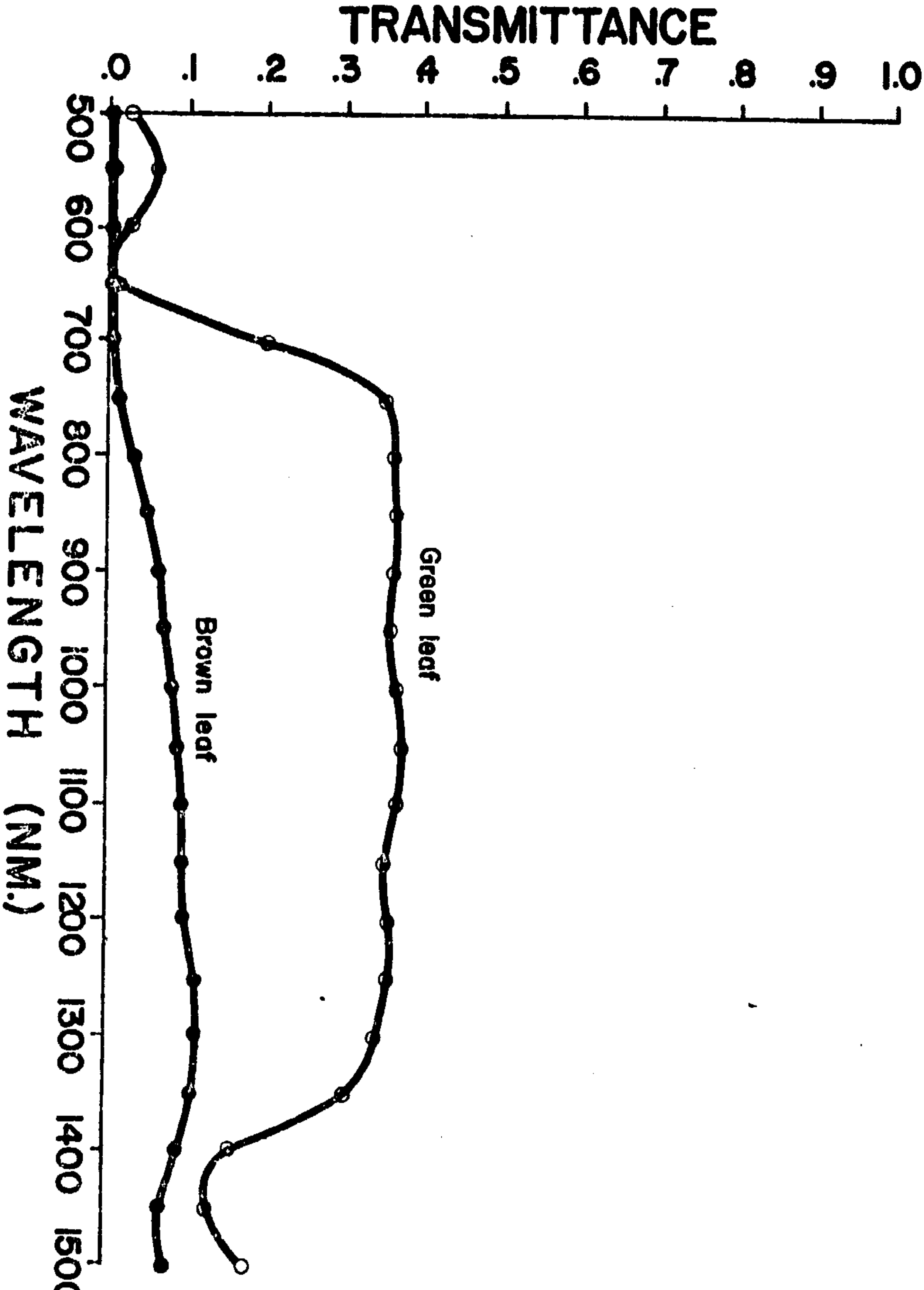

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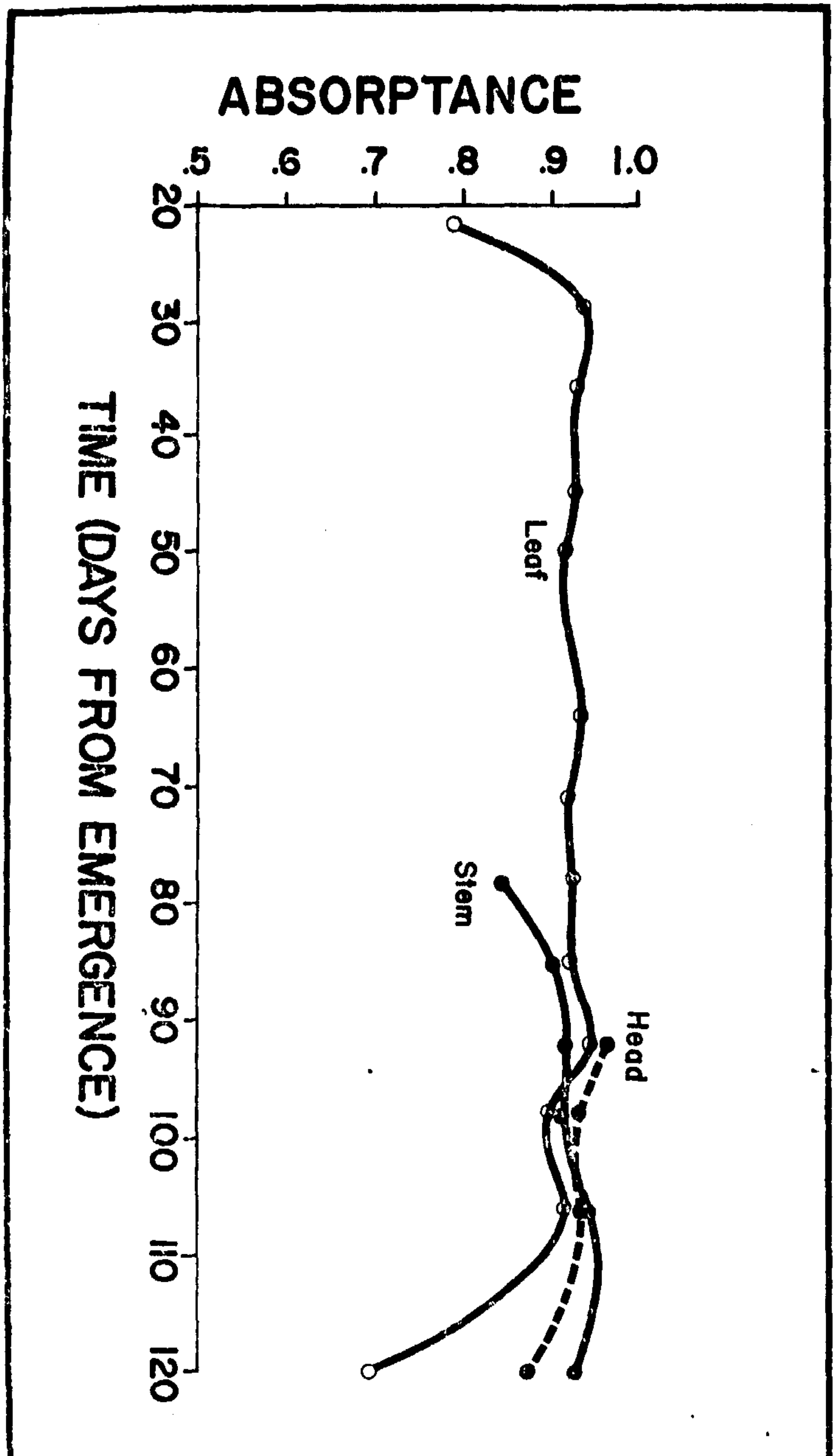

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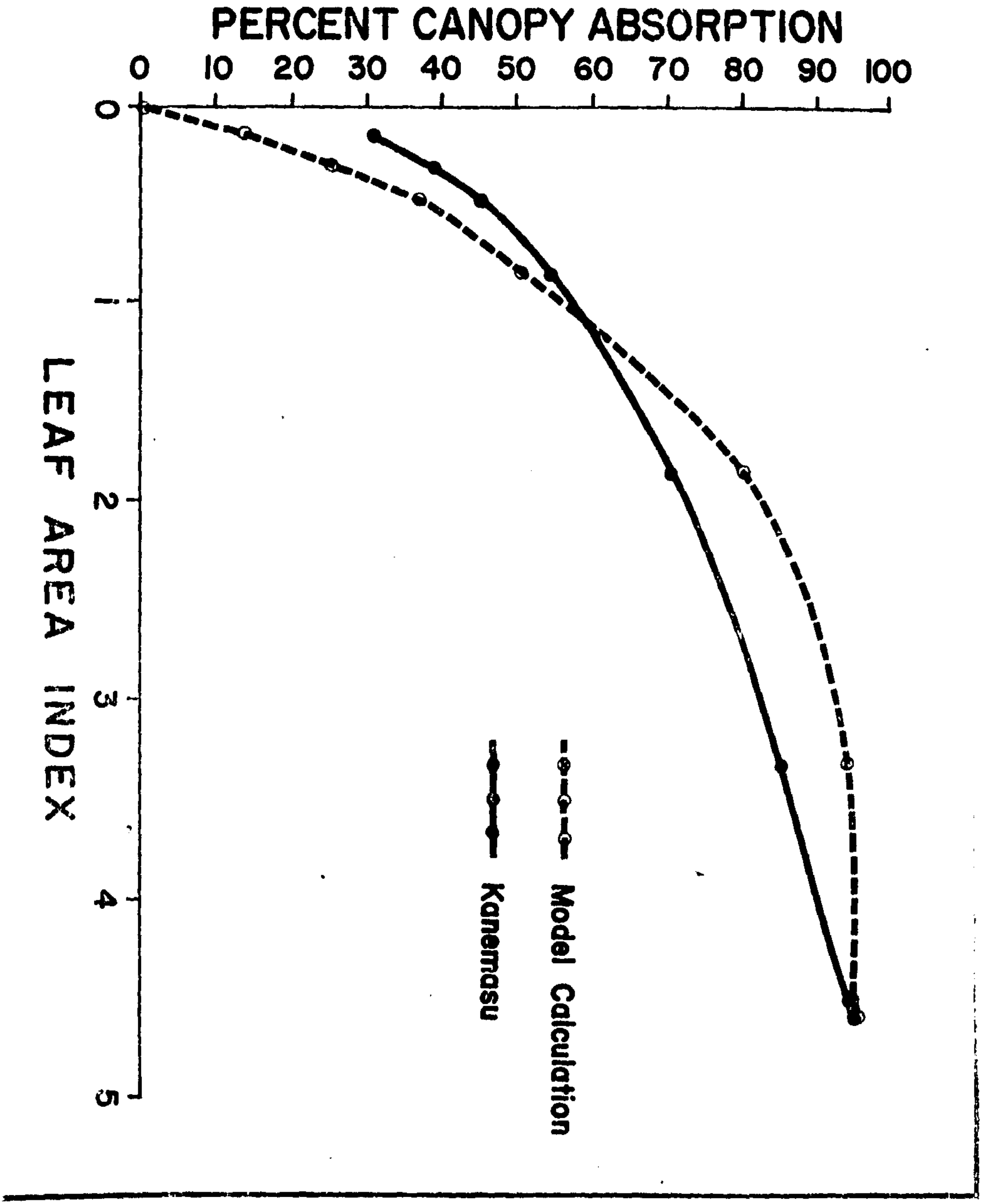

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