# DERIVATION OF LEAF-AREA INDEX FROM QUALITY OF LIGHT ON THE FOREST FLOOR

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*Abstract.* Leaf-area index of a forest can be measured by determining the ratio of light at 800 mμ to that at 675 mμ on the forest floor. It is based on the principle that leaves absorb relatively more red than infrared light, and therefore, the more leaves that are present in the canopy, the greater will be the ratio.

## INTRODUCTION

Ecosystem studies, such as those of productivity and chemical element cycling, require measurements of the quantity of leaves in the canopy. This quantity is often expressed as leaf-area index, that is, area of leaf per area of ground. In herbaceous communities it can be determined directly by clipping (Monsi and Saeki 1953), but forest measurements are more difficult to make. To estimate leaf-area index throughout a large area of tropical rain forest, Odum, Copeland, and Brown (1963) measured leaf-area index directly in 10 locations, correlated it with optical density measured with silicon solar cells, and then made optical density determinations throughout the forest.

There are two disadvantages in using optical density determined by solar cells as a measure of leaf-area index. One is practical, in that it is inconvenient in a field survey to have one cell above the canopy and the other in the investigator's hand, both of which must be read simultaneously, or nearly so. The second is theoretical, in that solar cells respond to light over a broad band of the spectrum including infrared, whereas the relatively greatest extinction of light occurs in the chlorophyll absorption band. Much of the light recorded by a solar cell on the forest floor is due to scattered light of wavelengths other than the chlorophyll absorption band. The quantity of this scattered light could be influenced by shape, orientation, and spacing of canopy leaves.

This paper presents an indirect method of measuring leaf-area index. The method may be superior to the optical density method.

## THEORY

Intensity of red light reaching the canopy is slightly greater than that of near infrared, but on the forest floor the relative intensity of the infrared is many times greater (Fig. 1, Federer and Tanner 1966) due to the selective absorption of radiation by leaf pigments. The more leaves that are present, the greater will be the difference in red and infrared radiation at the forest floor.

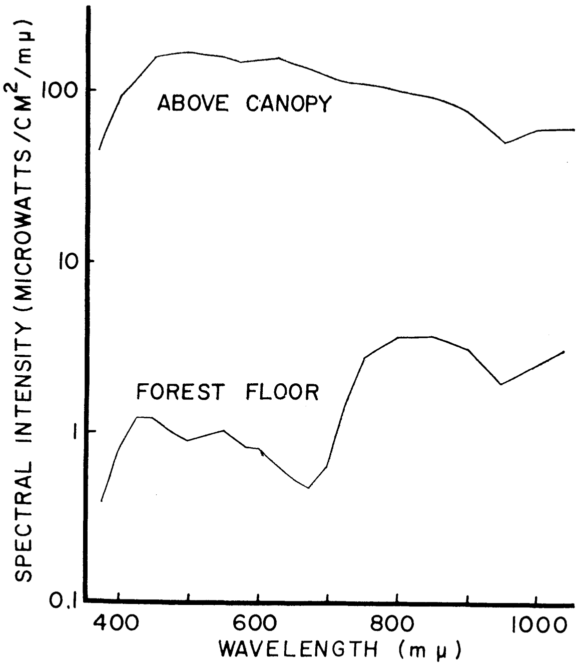


FIG. 1. Intensity of radiation vs. wavelength, measured above the canopy at noon on Nov. 16, 1967, and on the forest floor a few minutes later.

The intensities of infrared and red light can be expressed as a ratio, and this ratio can be calibrated with leaf-area index measured directly at several points in a forest. Leaf-area index throughout the entire forest can then be derived from ratios measured at the forest floor. To maximize the ratio as leaf-area index increases, the ratio should be between light at 800 and 675 mμ. Absorption of light by the canopy is at a maximum of 675 mμ and at a minimum at 800 mμ (Fig. 1).

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Since absorption of light is greatest at 675 mμ, scattering of light at this wavelength will be less than at most other wavelengths. The less scattering, the less the ratio is influenced by the angles and spacing of leaves, and hence, the more reliable the correlation of ratio and leaf-area index. However, even at 675 mμ there probably is some light scattering. To minimize this scattering, ratios should be measured only in direct sunlight and when the sun is high overhead. At 800 mμ reflectance and scattering is high, but here again, repeatability will probably be greatest with a clear sky and the sun overhead, rather than under cloudy skies where reflectance and scatter could be influenced by position and density of the cloud cover.

To use the ratio as a measure of leaf-area index within the forest, the ratio must be constant above the canopy. Although quantities of light vary during midday hours of sunny days, the ratio 800/675 remains almost constant (Fig. 2). The ratio is also independent of time of year (Table

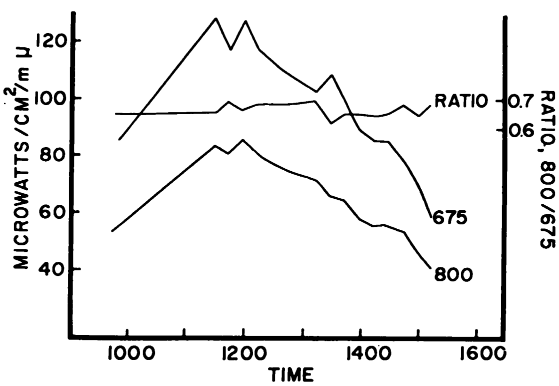


FIG. 2. Absolute intensity of light at wavelengths 800 and 675 mμ during the day, and ratio between these intensities.

1). The slight variations could be caused by human and instrumental factors. In any case, the variations are minute compared to changes due to the light passing through the canopy.

Since chlorophyll content per unit leaf area varies between species, the correlation between the ratio and leaf-area index will be valid only in the forest type where the correlation was accomplished. However, a correlation between ratio and chlorophyll concentration per square meter of forest floor could be valid for many vegetation types. With such a correlation, if milligrams of chlorophyll per square meter of leaf area were determined for a given vegetation type, leaf-area index could easily be derived by dividing chlorophyll concentration per square meter of forest floor by concentration per square meter of leaf area.

TABLE 1. Ratio between light at wavelengths 800 and 675 mμ above canopy on various dates (all readings made with no clouds covering the sun)

| Date | Number of readings | Average ratio |
|---|---|---|
| May 4, 1967 | 5 | 0.72±0.03 |
| May 10, 1967 | 1 | 0.71 |
| June 5, 1967 | 1 | 0.76 |
| June 16, 1967 | 1 | 0.75 |
| June 30, 1967 | 1 | 0.81 |
| July 5, 1967 | 1 | 0.70 |
| Sept. 15, 1967 | 1 | 0.81 |
| Sept. 18, 1967 | 2 | 0.72±0.01 |
| Oct. 18, 1967 | 1 | 0.76 |
| Nov. 16, 1967 | 15 | 0.66±0.02 |
| Dec. 5, 1967 | 2 | 0.77±0.02 |
| May 2, 1968 | 6 | 0.80±0.03 |
| July 1, 1968 | 4 | 0.69±0.04 |
| Average of all dates | | 0.74±0.05 |

## APPLICATION OF THEORY

Leaf-area index was measured at three locations in the Luquillo Experimental Forest near El Verde, Puerto Rico, by the following method. Scaffold-type towers were erected to a height equal to the top of the canopy, and with a minimum disturbance to the forest. A string with a weight on the end was thrown out from the top of each tower 16 times in such a way as to hook over a twig and then fall straight to the ground, and the number of leaves which each string touched was recorded. Leaf-area index at each site was taken to be the average number of leaves touched by the string on each throw. Leaf-area index at a fourth site in a ravine was taken to be 2.2, the value Odum, Copeland, and Brown (1963) determined for that site by clipping and measuring leaves.

Light readings at each location were made with a spectroradiometer manufactured by Instrument Specialties Co. The first wavelength was dialed in and a light intensity reading was taken. Immediately, the second wavelength was dialed, and a second reading taken. The process took about 15 sec. Since the ratio method proposed here assumes that both readings are made simultaneously, the first wavelength was dialed in a second time to assure that the intensity had not changed while the second reading was being made. On clear, sunny days there was no measureable change.

The spectroradiometer was calibrated with a spectral standard lamp supplied by Instrument Specialties Co. All readings were corrected to absolute values, and the 800/675 ratio was calculated in the office some time after the field measurements were made.

Results of the correlation are given in Table 2 and Fig. 3. The equation for the regression line in Fig. 3 is

$$\log Y = 0.3813 + 0.0989X \quad (1)$$

where $Y$ is the ratio of light at the wavelengths 800 and 675 mμ and $X$ equals leaf-area index. Using a value of 340 mg chlorophyll A per square meter of leaf area for this forest (Odum, Copeland, and Brown 1963), the relation shown in Fig. 4 was derived. The equation here is

$$\log Y = 0.3813 + 0.0002908X \quad (2)$$

where $Y$ again is the ratio and $X$ is milligrams chlorophyll A per square meter of forest floor.

Equation 1 is probably not valid for values of leaf-area index less than one, since it is known from Table 1 that with a leaf-area index of zero, the ratio is 0.78.

If light scattering were not a factor, Fig. 4 could be used to determine chlorophyll A concentration in any forested area, and from this, leaf-area index could be derived, as previously described. Since the calibration was made in a broadleaf forest with the canopy top at about 65 ft and very little shrub vegetation, the closer another forest resembles this structure, the more applicable this relation will be.

Light readings were done in a systematic manner, and values were recorded regardless of whether a light speck fell on the meter, or whether a limb was in a direct line between the sun and the meter. As a result, individual ratios taken at a given site varied greatly, but the averages (Table 2) were almost perfectly correlated with leaf-area index (Fig. 3).

TABLE 2. Data for correlation between leaf-area index and light ratio, and leaf-area index determination for entire forest

| Site | Leaf-area index | Average light ratio, 800/675 mμ | Number of readings taken | Date of readings[c] |
|---|---|---|---|---|
| Slope | 6.68 | 10.57 | 16<br>16 | Aug. 15, 1968<br>Aug. 19, 1968 |
| Slope | 5.60 | 8.84 | 4<br>4<br>30 | May 2, 1968<br>July 23, 1968<br>Aug. 15, 1968 |
| Ridge | 8.60 | 17.37 | 10<br>16<br>8 | April 24, 1968<br>May 2, 1968<br>July 1, 1968 |
| Ravine | 2.2[a] | 3.98 | 32 | Aug. 22, 1968 |
| Total for[b] forest | 6.6 | 10.90 | 114<br>123<br>130 | April 24, 1968<br>May 2, 1968<br>July 26, 1968 |

[a]Value taken from Odum, Copeland, and Brown (1963)
[b]Correlation sites not included
[c]Time of readings always between 11:30 and 12:30

Average leaf-area index for the entire forest as determined by light ratios measured every 5 ft along three 600-ft transects was 6.6 (Table 2). Odum, Copeland, and Brown (1963) determined a value of 6.4 for the same forest by averaging leaf clippings in forest prisms.

When the sun is directly overhead, the amount of leaf biomass through which the solar radiation passes is a minimum, assuming that leaf blades always remain horizontal. As the angle between

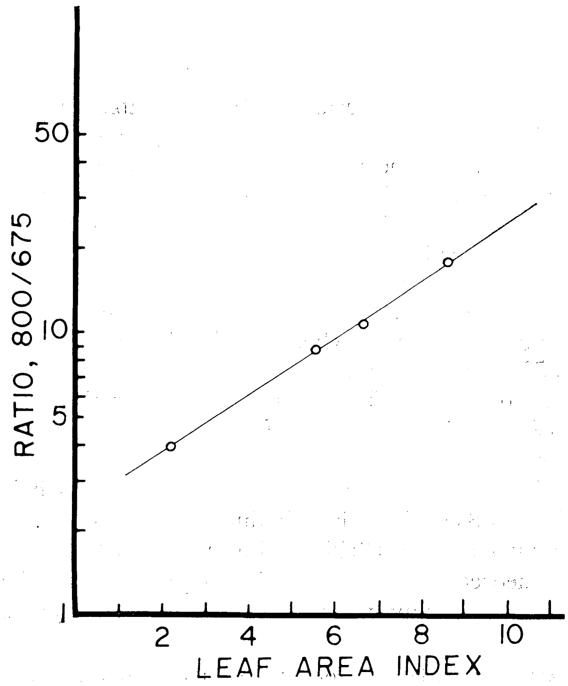


FIG. 3. Ratio of light intensities at 800 and 675 mμ measured on the forest floor, as a function of leaf-area index.

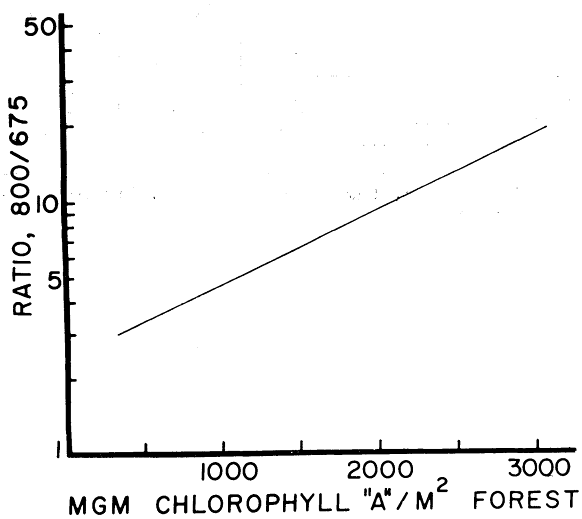


FIG. 4. Relation between ratio of light intensities at 800 and 675 mμ measured on the forest floor and milligrams of chlorophyll A per square meter of the forest.

the point directly overhead and the sun increases (angle $\alpha$), the amount of leaf biomass through which the solar radiation must pass increases. With increased biomass, the light ratio increases, and the leaf-area index calculated according to equation (1) also increases. This leaf-area index can be corrected to the leaf-area index obtained when the sun is directly overhead, by the following formula:

$$\text{Cosine } \alpha = \frac{\text{corrected leaf-area index}}{\text{observed leaf-area index}} \tag{3}$$

In Table 2 the maximum $\alpha$ for the dates of readings is 5°, as determined from a table of sun declinations (U.S. Naval Oceanographic Office 1964). Since the cosine of 5° is .996, the observed leaf-area index is virtually the same as the corrected leaf-area index, and in Table 2 no correction was made.

To check whether the light ratio method is accurate when $\alpha$ is large, ratios were determined at noon on Dec. 5, when $\alpha$ is 40° in Puerto Rico (22°S declination of sun plus 18°N latitude of Puerto Rico). The average of five ratios was 26.2, and the observed leaf-area index was calculated (equation (1)) to be 10.48. The corrected leaf-area index (equation (3)) is 8.06, which is close to 8.60, the value obtained at the site during summer months ("ridge" site in Table 2).

Theoretically, corrected leaf-area index can be obtained for any value of $\alpha$. However, as $\alpha$ nears 90°, relatively more red light is reflected from the leaves than infrared (Table 3), thus changing the ratio and the observed leaf-area index. Therefore, actual determinations of leaf-area index of a forest by the ratio method and correlation of ratio with leaf-area index should be accomplished with approximately the same $\alpha$.

TABLE 3. Reflectance of light by the canopy at three times on April 23, 1969

| Time | [a] | Percentage reflected | |
|---|---|---|---|
| | | 675 mμ | 800 mμ |
| 12:15 | 6° | 2.8 | 2.5 |
| 15:00 | 40° | 7.0 | 4.6 |
| 17:00 | 75° | 15.0 | 4.0 |

[a]Angle between the point directly overhead and the sun; determined by protractor as described in text.

While $\alpha$ is easy to obtain from a table of sun declinations when the sun is at its high point of the day, $\alpha$ at other times during the day is difficult to calculate. It is easier to measure it directly in the field. The accuracy of a transit is not really required for this measurement. A suitable device can be made by hanging a weighted string on a protractor, sighting the sun along the straight edge of the protractor, and reading the angle where the string crosses the protractor scale.

Cloudy skies are not suitable for using the ratio method of determining leaf-area index for two reasons. First, the thickness of the cloud cover could change without the observer on the forest floor being aware of a change in incoming light intensity. Secondly, with relatively more diffuse light entering the forest under cloudy conditions, there is more light scattering, and consequently the correlation is less reliable.

Although the ratio method for determining leaf-area index of a forest has limitations, they probably are not greater than the limitations of other methods, and the procedure for using the method is relatively quick.

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