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Influence of Stand Geometry on Light Interception and Net Photosynthesis in Cotton[1]

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ABSTRACT

The following geometric variables interact to determine the nature of shade patterns in row crops: solar altitude, the angle of the row with respect to the solar azimuth, plant size and planting pattern. Great change during the day was observed in the relative percent interception in all stands when the crop was young. In the early morning and late afternoon NS rows intercepted more light than EW rows. Percent interception began to level off at a leaf area index of about 3 in the conventionally planted cotton. Little or no convergence in the percent interception vs. LAI curves for noon and noon ± 5 hours was noted in the NS-skip cotton up to an LAI of 4 on a per planted acre basis. This indicates that expenditure of net photosynthate in the further elaboration of new leaf tissue would be a good investment as long as the fruit ultimately produced by the plant would have time to mature. Row direction had no significant effect on the total daily net photosynthesis by cotton conventionally planted in 40-inch rows. On a per planted acre basis the NS-skip planted cotton consistently outperformed the NS-solid stand and the EW-skip planted stand. In all of the stands the daily time course of net photosynthesis paralleled very closely the course of interception of solar energy. The light data from a flat surface receiver may be adjusted for percent interception by any stand, regardless of geometry, to give an accurate prediction of net photosynthesis.

THE dry matter yield of any crop may be obtained from the expression,

$$Y = \int_{t_1}^{t_2} (\text{net P})\, dt$$

where Y is the total dry weight of the plant, t is time, t_1 and t_2 being the planting and harvest dates, respectively, and net P is the rate of net photosynthesis by the stand. In many crops, e.g., grains and forages, this curve is sigmoid in nature and the base is exponential because of the rapid elaboration of leaf tissue. Cotton, however, is an indeterminant fruiting plant, and if the base of the curve is exponential, it will remain so for a shorter period of time. Nichiporovich,[4] Murata (8), and Hesketh et. al. (6) have suggested that in order to obtain maximum seasonal yields the leaf area, i.e., the light intercepting-photosynthesizing tissue, should be expanded as rapidly as possible after planting.

Kasanaga and Monsi (7), Davidson and Philip (4), and Saeki (9) have found that light is attenuated in a stand in a manner predicted by Beers' law. This attenuation is typically stated as:

$$I/I_o = e^{-NA}$$

where I is the average light intensity at the leaf surface, I_o is the horizontal light intensity above the stand, A is the leaf area index above the plane in which I is measured, and N is an extinction coefficient which depends on many things such as chlorophyll concentration in the leaf, leaf angle, leaf shape, etc. This model is valuable in that it requires the investigator in search of maximum yields to evaluate the A and N terms. It has been pointed out, however (2), that the above model is over simplified even in the small grain and forage crop stands for which it was proposed. The model is adequate at noon, but obviously angle of incidence is a prime factor causing the horizontal radiation flux density to vary. At angles of incidence, a, greater than zero degrees from the normal, both N and A in the equation vary. The extinction coefficient, N, varies because the stems (especially in grasses) absorb light. The leaf area traversed varies and can no longer be represented by the leaf area index, A. This term might better be approximated by A sec a. In young row crops the model may be expected to break down completely, especially in skip row plantings, where some rows at regular intervals are left unplanted. In such crops and in orchards the method of measurement of light and accounting for interception has been the subject of some discussion. Gulyaev (5) has pointed out that the kind of receiver (flat or spherical) is a matter of some controversy, and that certain research workers are inclined to show exclusive preference for the sphere. After a careful mathematical treatment however, he showed that use of a spherical receiver is not desirable even in relatively small communities.

Very high correlations have been reported between rates of net photosynthesis and solar radiation measured with an Eppley pyrheliometer[5] in corn (3) and cotton (1) stands which were planted in north-south 40-inch rows. The relationship was linear in the case of cotton and both crops intercepted greater than 92% of the incident short wave radiation. As Yamada et al. (10) have pointed out, these high correlations will be lost if there is a diurnal change in either photosynthetic efficiency or the rate of interception. The purpose of the present investigation was to develop means of measuring and accounting for the light variable in young row crops.

MATERIALS AND METHODS

The Crop. On April 30 and May 1 (1964) the south 1/3 of a 9.6-acre field was planted in 40-inch rows running east-west, and the remainder was planted in rows running north-south. The variety of cotton planted was 'Deltapine Smoothleaf' (*Gossypium hirsutum* L.). The rows were oriented by means of a transit. At planting, fertilizer was applied in bands at rates of 78, 24, 44, and 26 pounds per acre of N, P, K, and Mg, respectively. The crop was side-dressed with 32 pounds of N per acre. Each section of the field contained several plot areas

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[4] Nichiporovich, A. A., Photosynthesis and the theory of obtaining high crop yields. Read 4 June 1954, 15th Timiryazev Lecture Izdat. An SSSR, Moscow, 1956.

[5] Mention of a proprietary product does not necessarily imply endorsement of this product by USDA.

planted in a 2×2 skip row pattern. Stated differently, these areas contained planted pairs of 40-inch rows alternating with unplanted pairs of 40-inch rows. Soil moixture tensions less than 0.6 bar were maintained in this field by means of furrow irrigation.

The Measurement of Light Interception. An Eppley pyrheliometer was mounted in an exposed position for the conventional measurement of solar plus sky radiation. A second Eppley pyrheliometer was mounted on a traverse arrangement. This device was dug in so that the sensing surface of the pyrheliometer was at ground level. It was then carefully leveled.

The pyrheliometer was pulled through four 40-inch cotton rows at constant speed and in a manner which did not disturb the stand. Approximately 18 minutes were required for a complete cycle. The millivolt outputs from both pyrheliometers were integrated over 15-minute intervals. Percent interception was calculated as follows:

$$\%I = 100\ (1 - Rg/Ri)$$

where Ri is the short wave radiation incident above the crop (ly/min.) and Rg is the radiation incident at ground level. A full day of clear weather data was collected at each set up. The instrument was rotated through the various crop stands in the following order: north-south solid, north-south skip, east-west solid, east-west skip. This schedule was begun when the solid planted crop had a leaf area index of 0.5 and continued until a LAI of 2.12 in the EW rows and 3.08 in the NS rows was obtained.

Net Photosynthesis Measurements. The semiclosed system described in a previous paper (1) was used for measurement of net photosynthesis. The data were expressed as the net amount of CO_2 assimilated per square decimeter ground area per minute. This system was operated at an air temperature of 30 ± 3 C and a soil moisture level near field capacity. The chamber was moved from one stand to another in the same order as the light interception equipment.

Reduction of the Data. The following steps were taken in the reduction of the data:

(a) The local standard time of each observation (assimilation and interception) was converted to true solar time. This relationship depends on the longitude of the observer and changes with the date (solar declination).

(b) The solar altitude and solar azimuth were calculated for each solar time and declination from the following equations:

$$\sin a = \sin \Phi \sin \delta + \cos \Phi \cos \delta \cos h$$
$$\sin \alpha = -(\cos \delta \sin h)/\cos a$$

where a = altitude of the sun (angular elevation above the horizon), Φ = latitude of the observer, δ = declination of the sun, h = hour angle of the sun (angular distance from the meridian of the observer), and α = azimuth of the sun (measured from north).

(c) It was found convenient to define a new angle, σ, as being equal to the smallest angular distance between the row direction and the azimuth.

(d) The leaf area indexes were calculated for each track and chamber setup using the formula A = length $\times$ greatest width $\times$ 0.72 to obtain the area of each leaf. When the stands reached LAIs greater than one it became impractical to measure all of the leaves. Then a sampling technique was developed in which all the leaves on all the plants were counted. The plants were then grouped in five classes according to the number of leaves, and the leaves of the median plant of each class were measured. These data were used to calculate an average leaf size for that class. The total leaf area for each class was obtained by multiplying the number of leaves in the class by the average leaf size. This method undoubtedly resulted in large errors in LAI determination.

(e) Four regression models were fitted to obtain the following relationships: net photosynthesis as a function of a, σ, LAI, and Ri, both in the solid and in the skip-row stands; and percent interception as a function of a, σ, and LAI, also in the solid and skip-row stands.

The regression model to which each of the two sets of net photosynthesis data were fitted is as follows:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_1^2 + b_6X_2^2 + b_7X_3^2 + b_8X_4^2 + b_9X_1X_2 + b_{10}X_1X_3 + b_{11}X_1X_4 + b_{12}X_2X_3 + b_{13}X_2X_4 + b_{14}X_3X_4 + b_{15}X_1X_2X_3 + b_{16}X_1X_2X_4 + b_{17}X_1X_3X_4 + b_{18}X_2X_3X_4 + b_{19}X_1X_2X_3X_4,$$

where X_1 is Ri, X_2 is solar altitude, X_3 is the angle sigma and X_4 is the leaf area index. The regression model to which each of the two sets of interception data were fitted is as follows:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_1^2 + b_5X_2^2 + b_6X_3^2 + b_7X_1X_2 + b_8X_1X_3 + b_9X_2X_3 + b_{10}X_1X_2X_3,$$

where X_1 is the leaf area index, X_2 is solar altitude and X_3 is the angle sigma. It may be noted that Ri in the analyses of the net photosynthesis data is not totally independent, i.e., it depends on a, and σ as well as cloud cover.

(f) Points were calculated from these models assuming values of the angles corresponding to the solar time, light intensity, and leaf area index within the range of the data for each stand. These points were used in plotting the percent interception and net photosynthesis curves presented in Figures 3, 4, 5, and 6.

RESULTS AND DISCUSSION

The ideal light sensor for interception measurements of the present type would be small (not over an inch in diameter) and would have an action spectrum similar to that of a green leaf. The Eppley pyrheliometer has a flat response in the region 0.3 to 2.5 μ. Calculations based on the best data available in the literature (11), assuming the action spectrum is roughly similar to the absorption spectrum, indicate that this instrument may overestimate the energy available for photosynthesis in the shade of a leaf by as much as 12% due to the transmission of infrared radiation. Although this produces a very small error on an absolute energy basis, it is an undesirable feature of this equipment.

The change in solar altitude and solar azimuth with time is shown in Fig. 1. The azimuth is graphed in degrees north or south of east. The sun rises and sets about 20° north of east on June 13 at State College, Miss. It is due east at 0845 and due west at 1515 hours solar time. It is due south at solar noon. An azimuth effect causing cross row shade in east-west (EW) rows will cause mutual shading (shadows cast down the row) in north-south (NS) rows and vice versa. Mutual shading is to be considered undesirable. It may reduce yield directly by reducing the light available for photosynthesis and indirectly by allowing radiation to pass directly to the soil where it may be dissipated as latent heat, removing water from the root zone. Preliminary visual observations suggested that the NS rows would have a slight daily advantage in light interception. These observations also revealed that all

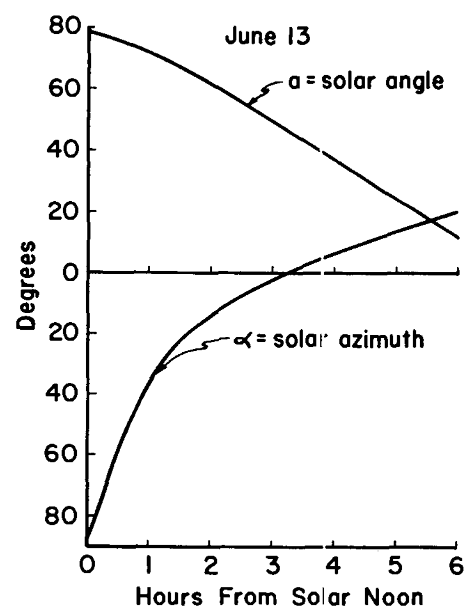

Figure 1. Path of the sun at State College, Mississippi.

of the stands were markedly heliotropic.

The change in shade pattern with time, LAI, and planting arrangement is shown in Fig. 2. Each point in this figure is the average of the morning and afternoon interception measurements on the day when the leaf area index was that given under "LAI." In the skip row cotton the leaf area indexes were calculated on a total acreage basis, so the curves labeled 1.52 and 1.55 represent rather large cotton plants. On a per planted acre basis the NS-skip stand would have an LAI of 3.04 and at 6 hours from noon would be intercepting approximately 120% of the incident light. These skip rows continued lateral elaboration of leaves until the NS stand had an LAI of 6 on a per planted acre basis.

The regression models accounted for 84% of the variation in the interception data from the solid planting and 62% in the data from the skip planting. The standard errors of estimate were 11% and 9% interception, respectively. The experimental error was relatively larger in the skip row data because 18 minutes were required for a revolution of the intrument through the stand, while the integrals were made over 15 minutes. This resulted in a random sampling error and will not affect the shapes and locations of the curves obtained from the model. The analysis of these data revealed the following:

(a) There was a great change during the day in the relative percent interception by all stands when the crop was young.

(b) Early in the morning and late in the afternoon the NS rows intercepted more light than the EW rows. This effect was small in the solid cotton but quite distinct in the skip plantings. All NS plantings intercepted more light at noon than did the EW plantings.

(c) All the NS rows reached a minimum of interception at about two hours from solar noon.

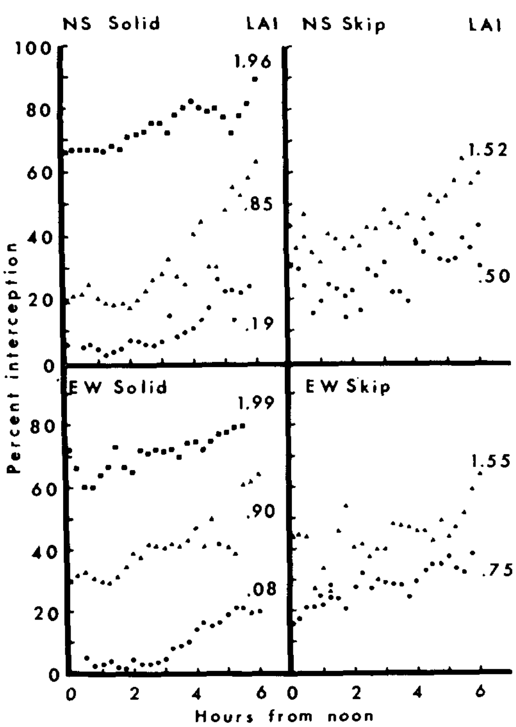

Figure 2. Percent interception of solar radiation vs. time from solar noon in 4 cotton stands of various leaf area indexes.

(d) The EW rows had a pronounced minimum at noon.

The regression equations were used to calculate the points from which the curves in Fig. 3 were drawn. It would be expected that the interception of light would increase with LAI to a certain point and then begin to level off. This is demonstrated by the NS-solid data. It would also be expected that the two curves (noon and noon ± 5 hours) for each stand would tend to converge with increasing LAI, at some maximum interception. This effect is quite noticeable in the EW stands. It occurred to some extent in the NS-solid cotton, but was almost negligible in the NS-skip stand over the range of LAIs measured. A lack of convergence, as in the NS-skip stand, indicates that expenditure of net photosynthate in the further elaboration of new leaf tissue would be a good investment assuming, or as long as, the fruit ultimately produced by the expanded plant will have time to mature.

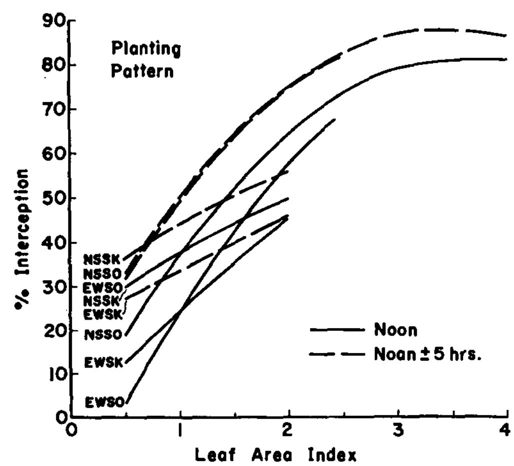

Figure 3. Percent interception of solar radiation vs. leaf area index in cotton in several planting patterns. NSSK = north-south skip rows, NSSO = north-south solid rows, EWSK = east-west skip rows, and EWSO = east-west solid rows.

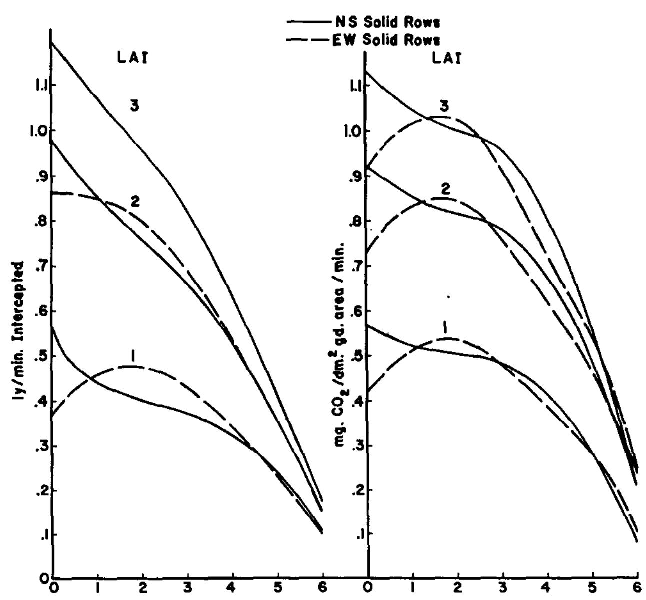

Figure 4. Intercepted short wave energy and net photosynthesis vs. time from solar noon in conventionally planted cotton.

For these interception data to be evaluated in terms of their effect on yield they must be converted to intercepted energy. This has been done for the solid plantings in the left hand side of Fig. 4 by multiplying percent interception calculated from the regression models by the energy available on a typical clear day in mid-June. The corresponding net photosynthesis data have been plotted in the right hand side of Fig. 4. It was noted above that the Ri variable in the regression analysis of these photosynthesis data was not totally independent, but depended on the sun angle as well as on the amount of cloud cover. This feature of the data allowed a mathematical separation of these two effects on the rates of net photosynthesis by the stands. The regression model explained 82% of the variation in the net photosynthesis and the standard error of estimate was 0.137 mg CO_2/dm^2 ground area/min., but there were no significant differences in the areas under any of these pairs of curves. In other words, in this conventionally planted cotton, row direction did not have any appreciable effect on the total daily amount of net photosynthate produced at any given plant size. There is a notable similarity in the shapes of the assimilation and intercepted energy curves.

Similar data representing the skip row stands are presented in Fig. 5. The regression model explained 74% of the variation in these net photosynthesis data, and the standard error of estimate was 0.166 mg $CO_2/dm^2/min$. The same general pattern occurred, but here the NS rows consistently outperformed the EW rows. The difference in the areas under the net photosynthesis curves is 32% at an LAI of 0.5 and 22% at an LAI of 1.5 (total acreage basis). These differences are slightly greater than would be predicted from the interception data. This may have been due in part to the heliotropism and the resulting arrangements of the leaves. The middles tended to remain much more open in the EW stands. In any case it suggests that a given LAI will be reached much faster in the NS skip rows and should result in a considerable increase in yield even though the base of the growth curve in cotton may not be exponential in nature. It might also be noted that both of these skip stands intercepted more light on a per planted acre basis than did the solid stands. This did not, however, result in growth advantage in the EW-skip rows. At an LAI of 1.0 (per planted acre basis) the NS-skip

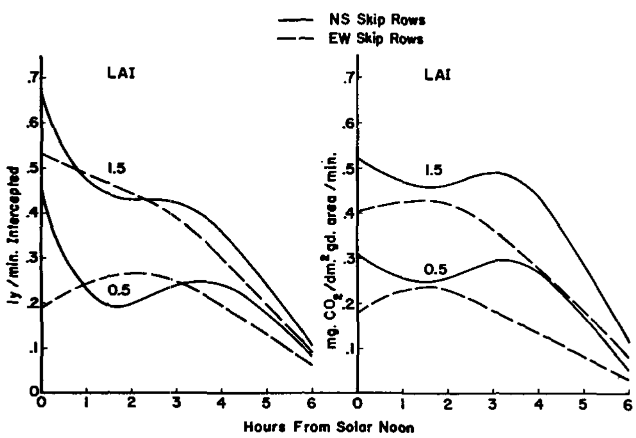

Figure 5. Intercepted short wave energy and net photosynthesis vs. time from solar noon in skip-row cotton. Leaf area indexes are based on total ground area.

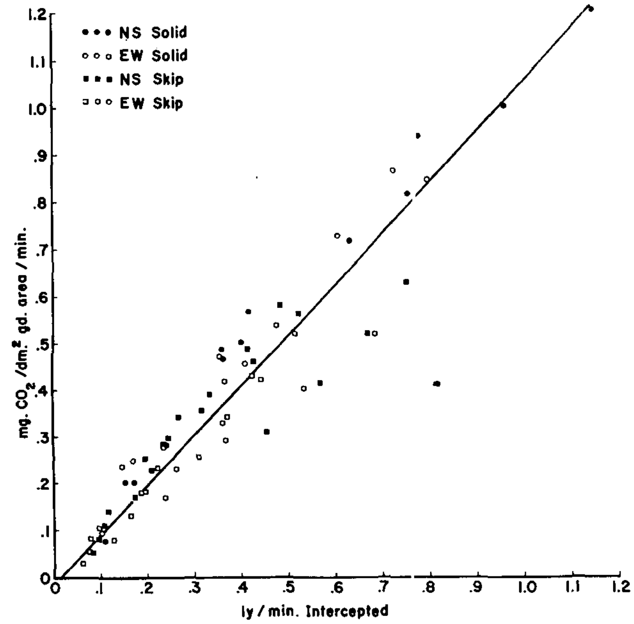

Figure 6. Net photosynthesis vs. intercepted short wave energy.

cotton had an 11% greater daily growth rate than did the NS-conventionally planted cotton. Thus, of the four stand arrangements the young NS-skip stand intercepted the most light and developed most rapidly.

The points used in drawing the curves in Figs. 4 and 5 have been used to plot net photosynthesis vs. intercepted short wave energy in Fig. 6. No notation of LAI or of time from solar noon has been made, but the stands are identified by the points. It is evident that regardless of plant size, sun angle or planting pattern the growth rate is directly proportional to the amount of light intercepted. Thus, a simple adjustment for percent interception yields the same linear response curve as was reported previously (1) for a mature cotton stand. In predicting the yielding potential of a crop surface one must account for the light variable. Direct measurement of light interception is technically simpler and more accurate than methods involving calculations based on, and requiring, leaf area measurements.

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