Published March, 1985

Penetration of Radiation into Cotton Crop Canopies[1]

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ABSTRACT

The penetration of radiation into cotton (*Gossypium hirsutum* L., 'Acala SJ-2') canopies was investigated in two field experiments in Negba (1980, irrigated by sprinklers), and in Nahal-Oz (1981, three irrigation treatments by a drip system). Photosynthetically active radiation (PAR) below the canopy was measured by a sensor moving on a 2 m track across the rows and integrated for periods of 30 min. The PAR was also measured above the canopy, and the percent of penetration was calculated. Plant height and leaf area index (LAI) were measured together with the radiation measurements. A high correlation was found between plant height and LAI, and both were highly correlated with radiation penetration. Plant height was found to be more useful than LAI as a predictor of radiation penetration, because its measurement in the field is more convenient. During periods of moisture stress, radiation penetration was usually lower than predicted by plant height. An examination of our data by using a model revealed that plant width was an important factor determining radiation penetration. The model accurately predicted radiation penetration into the canopy, provided that reliable estimates of essential plant parameters (e.g., plant height and width, LAI, and leaf angle distribution) had been input. Increased growth in height was usually associated with high rates of irrigation, whereas plant width was not. Plant width increased abruptly as soon as the first bolls began to develop, and this was followed by a rapid decrease in radiation penetration.

***Additional index words:* *Gossypium hirsutum* L., Irrigation, Leaf area index, Modeling, Moisture stress, PAR, Plant height, Plant width.**

THE absorption of solar radiation by a plant canopy is a major factor determining its rate of photosynthesis, and therefore also its rates of growth and development. There are very scarce empirical data available of light interception by cotton canopies (2,6,11,18) or other row crops, such as sorghum [*Sorghum bicolor* (L.) Moench] (2, 3, 5, 7, 10) or maize (*Zea mays* L.) (2, 15, 17).

Several methods for measuring radiation interception in row crops were compared by Adams and Arkin (2). Most of these methods, with the exception of the meter stick method, were found to be time-consuming and to require expensive equipment. Baker and Meyer (6) examined the relationship between radiation interception and the leaf area index (LAI) of cotton plants. Several crop simulation models base the estimate of radiation interception on either plant height or LAI. Lemeur and Blad (16) reviewed the various models used to predict radiation penetration through a canopy. The classical concept of exponential light attenuation with depth (Beer's law) has been adopted in many models. Monteith (20) pointed out some weaknesses of this assumption and introduced the concept of sunflecks. Anderson (4) examined the constancy of the extinction coefficient and concluded that it was affected by the ratio of diffuse to direct radiation, and by the leaf inclination angle. Acock et al. (1) modified Beer's law for random, regular and clumped leaf distributions. It was also reported that the extinction coefficient was sensitive to the sun elevation angle (7, 11, 15), leaf angle

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distribution (11, 15), planting density (17), location of foliage within the canopy (11, 19), and leaf size distribution (19). In row crops, the extinction coefficient is also affected by row spacing (7) and by row azimuth.

Another modeling approach, applied mainly to row crops, is the geometrical compartmentization of the canopy. Jackson and Palmer (12) examined "hedgerow" models with different geometrical configurations. Others (3, 10, 21) modeled light interception in sorghum as a hedgerow with a rectangular cross section, whereas Arkin et al. (5) examined "cube" and "square plane" models. Fukai and Loomis (11) divided the canopy into rectangular compartments and observed the distribution of leaf area, leaf inclination angle and leaf azimuth angle for each compartment. Allen (3) modified the hedgerow model by including a two dimensional distribution of leaf area density in the canopy, and by calculating a "gap-factor" for direct and diffuse radiation. On the other hand, Fuchs and Stanhill (10) concluded that the distribution and posture of leaves within the canopy had a very small effect on radiation interception.

Mann et al. (18) combined a geometrical model with a probability model for light extinction within the canopy, which was assumed to be shaped as an ellipsoid. Plant height, plant width, LAI, row spacing and plant density within the rows, as well as the row azimuth direction, are some of the parameters that have to be specified for their model. They assumed that a certain proportion of the leaf area is heliotropic, and the remainder is radially symmetrical with a known leaf inclination distribution.

The objective of this work was to examine and evaluate methods which may accurately estimate radiation penetration from some easily measured plant parameters. Radiation penetration is an important parameter for the estimation of canopy photosynthesis as well as evapotranspiration rates.

MATERIALS AND METHODS

The experimental data are based on two field trials. Trial 1 was planted in Negba, in the southern coastal plain of Israel, on 1 Apr. 1980. The field was irrigated by sprinklers as follows : 90 mm on 12 June, 100 mm on 1 July, 90 mm on 20 July, and 90 mm on 9 August. Trial 2 was planted in Nahal-Oz, in the northwestern part of the Negev region of Israel, on 31 Mar. 1981. It was irrigated by a drip system twice weekly, from 14 June to 31 August. The trial consisted of three different rates of water application. The normal treatment (NOR) followed the recommended practice in the area, whereas in the low (L) and high (H) treatments less and more water, respectively, was applied. The total seasonal amounts of irrigation water were 330, 380, and 420 mm in treatments L, NOR, and H, respectively. In both locations, maximum temperatures were 28 to 30°C and minimum temperatures were 16 to 20°C during the months of June, July and August.

The cultivar 'Acala SJ-2' of *Gossypium hirsutum* L. was used in both trials, and planted in north-south rows spaced 97 cm. There were on the average 11 plants m^{-1} row^{-1}. Photosynthetically active radiation (PAR), in the range of 400 to 700 nm, was measured by LI-190S quantum sensors. Two of these sensors were each mounted on a track, 2 m long, which was placed in a shallow trench, perpendicular to the plant rows. The sensors moved along the tracks, near ground level, at a speed of 2.2 cm s^{-1}. A third sensor was placed above the canopy. Each sensor was connected to a digital integrator, and the cumulative data were recorded at 30 min intervals. For each interval, radiation penetration was calculated as the ratio of ground-level to above-canopy radiation. These ratios were averaged to obtain the daily values of radiation penetration.

At the end of each day, all plants from 3 m^2 at each measuring location were harvested and taken to the laboratory, where plant height was measured. Leaf area was measured with a photocell-based planimeter (Hayashi Denko Co., Tokyo, Japan type AAM-5). All the leaves were measured at the beginning of the season. Later, a subsample was taken from each sample, to determine the ratio of leaf area to dry weight, and the leaf area was calculated from the dry weight of the whole sample.

RESULTS AND DISCUSSION

The vegetative development of cotton plants can be characterized by monitoring the plant height (Fig. 1), or the leaf area index (Fig. 2). The rate of vegetative growth was strongly affected by the irrigation regime (Figs. 1B, 2B). A strong correlation was found between plant height (H, cm) and LAI (L, m^2 m^{-2}). The following linear regression was found for the pooled data of both experiments :

$$L = -0.39 + 0.030 * H$$
$$(R^2 = 0.94, s_b = 0.0014) \quad [1]$$

This regression was not significantly different when each location or irrigation treatment were examined separately. Obviously, the linear relationship is not valid at the end of the season, when LAI decreases because of leaf abscission. This relationship is likely to be specific to the cultivar, as well as to some cultural methods, especially irrigation regime, row spacing and plant spacing within the row.

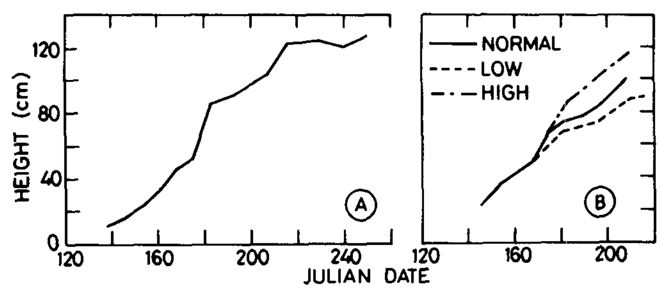

Fig. 1. Plant height in two field trials. A. Negba 1980. B. Nahal-Oz 1981, under three irrigation regimes.

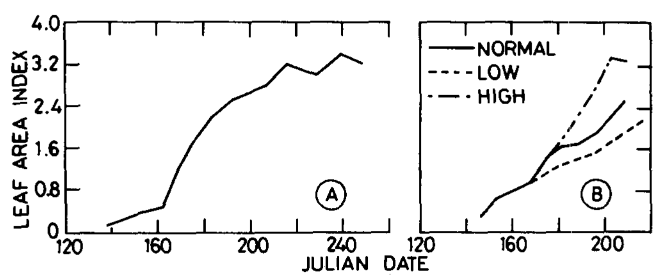

Fig. 2. Leaf area index in two field trials. A. Negba 1980. B. Nahal-Oz 1981, under three irrigation regimes.

Radiation penetration through the canopy, for a representative day, is given in Fig. 3. The sky was clear during most of the measurement period, and midday PAR exceeded 2000 μmol $m^{-2}s^{-1}$. Brief cloudy periods reduced the radiation intensity and also changed the ratio of diffuse to direct radiation. Maximum radiation penetration through the canopy was between 20 and 60%, depending on canopy height and structure. In the mornings and in the afternoons, radiation penetration was less than at noon, depending on the sun's elevation and azimuth angles. The irregularities in the radiation penetration curves were probably caused by changes in the ratio of diffuse to direct radiation, as well as by fluctuation of leaf orientation.

The average daily radiation penetration, for all the measurement dates, is given in Fig. 4. There was an average decrease of 1.3% per day , but this was not uniform throughout the season. There were some irregularities, probably associated with changes in radiation (cloudy days) or with modifications of canopy structure and leaf orientation, which may have been caused by moisture stress or other factors. At the end of the season, radiation penetration increased because of leaf abscission.

Average radiation penetration (P, %) was found to be highly correlated with either LAI (L, m^2 m^{-2}) or plant height (H, cm). The following linear regression equations were found for all the data:

$$P = 93.9 - 28.56 * L \quad (R^2 = 0.83,\ s_b = 2.61) \qquad [2]$$

$$P = 109.3 - 0.907 * H \quad (R^2 = 0.90,\ s_b = 0.060) \qquad [3]$$

The linear correlation of P with H was somewhat better than that of P with L. Also, the measurement of H in the field is more convenient and more accurate than that of L. It may therefore be concluded that plant height is a better predictor of radiation penetration than LAI. The relationship between average radiation penetration and plant height is given in Fig. 5. Generally, there is good agreement between measured and predicted radiation penetration. Relatively large deviations from the predicted values were found for plants 65 to 90 cm high. These deviations may be mainly ascribed to the effect of moisture stress, because stressed plants reached a certain height later than the unstressed ones, showing lower radiation penetration at the same height because of wider plants. Radiation penetration was also higher than predicted for late season observations in Negba (for plants higher than 120 cm), probably because of some leaf abscission. In some cases, radiation penetration was probably also affected by changes in leaf orientation.

For better prediction of radiation penetration, a more elaborate model may be needed. After examining available models in the literature, we chose the model of Mann et al. (18) and wrote a computer program for it. It was run for each day in which detailed measurements were made in Nahal-Oz, and the results were compared to the measured data. As input data for these runs we used the measured plant height and LAI values, and an estimated value for plant width. The model was run for a latitude of 32°, and north-south plant rows. The model also requires, as input data, the leaf area orientation distribution. This was assumed to change during the day, but to have a constant pattern throughout the season. The pattern that gave the best fit to the actual data, as determined by a series of preliminary runs of the model, is given in Fig. 6. The proportion of heliotropic leaves was assumed to be maximum at noon, whereas the proportion of horizontal leaves (0° to 10° elevation)

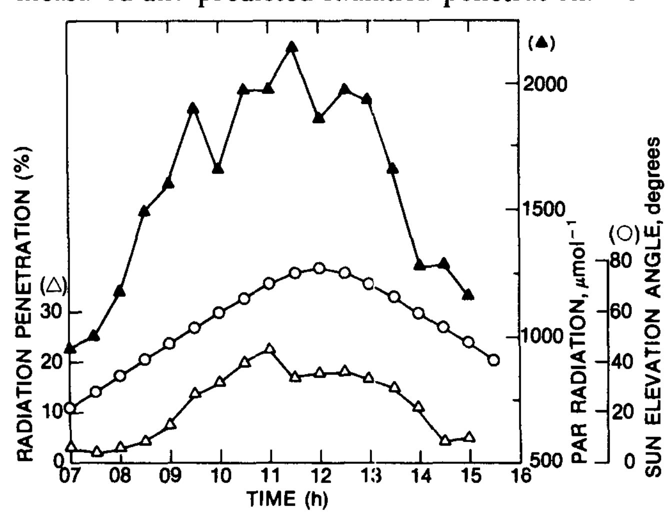

Fig. 3. PAR (▲), sun elevation angle (○), and radiation penetration through the canopy (△), 28 July 1981, Nahal-Oz, normal irrigation treatment. LAI 2.54, plant height 101 cm, and plant width 85 cm.

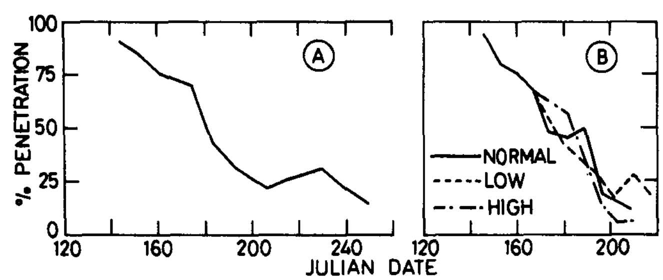

Fig. 4. Average daily percentages of PAR penetration through the canopy. A. Negba 1980. B. Nahal-Oz 1981, under three irrigation regimes.

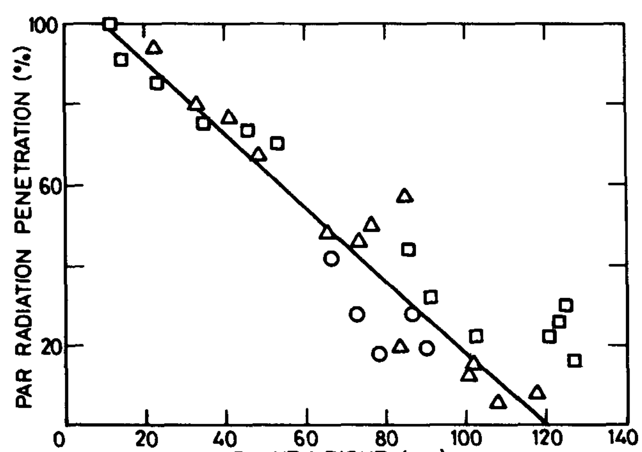

Fig. 5. The relationship between PAR penetration and plant height. □ -Negba ; ○ -Nahal-Oz, low irrigation; △ -Nahal-Oz, normal and high irrigation.

was minimum at noon. The proportion of 10° to 20° leaves increased somewhat in the afternoon, and the 20° to 30°, 30° to 40°, and 40° to 50° leaf angle groups remained at a constant proportion of 10% each.

The results of the model, as compared to the field measurements for nine representative days, are presented in Fig. 7. Generally, there is a good fit both at the beginning of the season (Fig. 7, A to C) and at its end (D to G), for the NOR and L treatments. Some deviations from the model may be explained by short cloudy periods, with an increased proportion of diffuse radiation, or by a temporary moisture stress causing drooping of the leaves. For the H treatment there was one day (Fig. 7, H) during which the measured radiation penetration was much higher than that predicted by the model, probably because of exceptionally erect growth.

The average daily values of radiation penetration, as predicted by Mann's model, are compared to the measured values from 13 days in Fig. 8. Model averages were calculated for the same time periods as

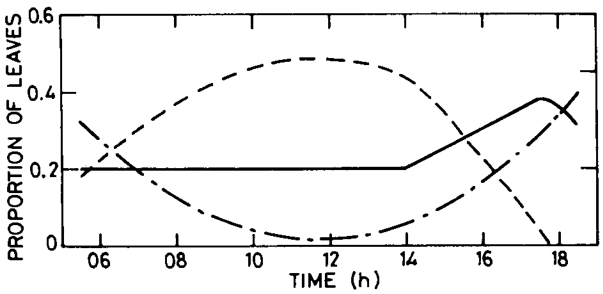

Fig. 6. Assumed leaf area orientation distributions, used for running the model of Mann et al. (18). — · — · — 0°-10°; ——— 10°-20°; — — — heliotropic leaves.

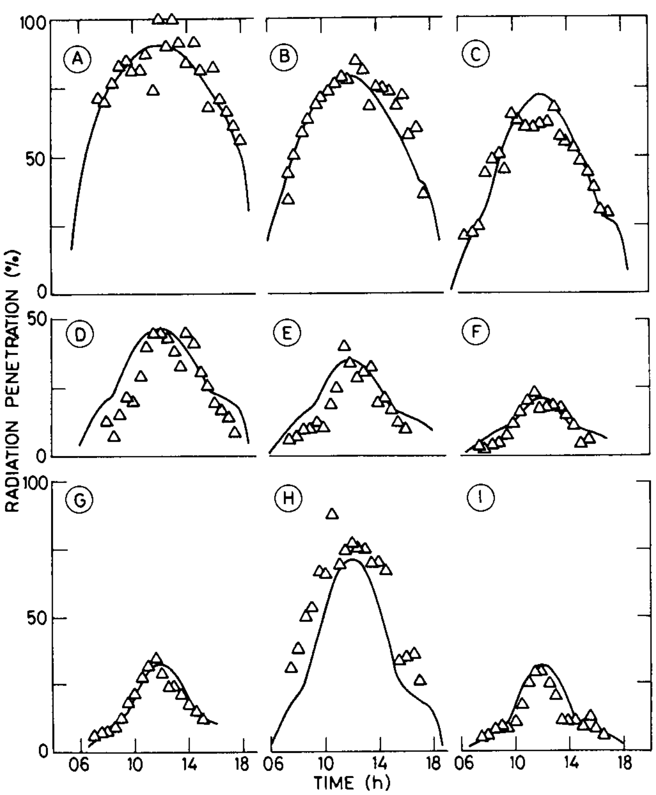

Fig. 7. The PAR penetration through the canopy, for some measuring dates, Nahal-Oz 1981, △ as measured, ——— as predicted by the model of Mann et al. (18). A. 2 June. B. 16 June. C. 23 June. D. 14 July. E. 16 July. F. 28 July. G. 5 August. H. 1 July. I. 15 July. G is low irrigation treatment, H and I are high irrigation treatment, and all the others are normal irrigation treatment. The following input values were used for A to I, respectively, in this figure : Plant height 34, 49, 66, 73, 84, 101, 90, 85, 102 cm; Plant width 13, 24, 30, 60, 72, 85, 72, 30, 70 cm; LAI 0.65, 0.95, 1.41, 1.52, 1.93, 2.54, 2.22, 1.81, 2.75.

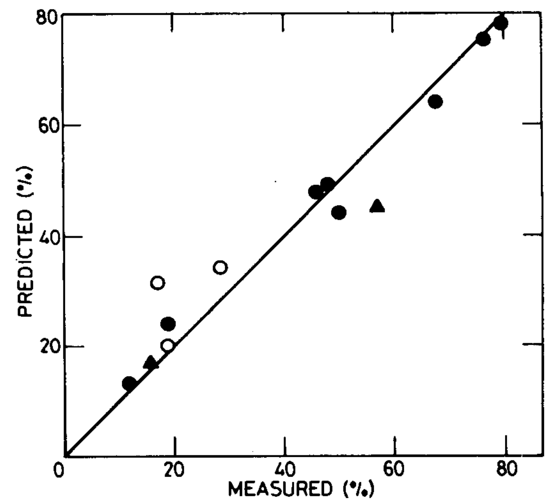

Fig. 8. Predicted and measured average daily values of PAR penetration, Nahal-Oz (1981) under low (○), normal (●), and high (▲) irrigation regimes.

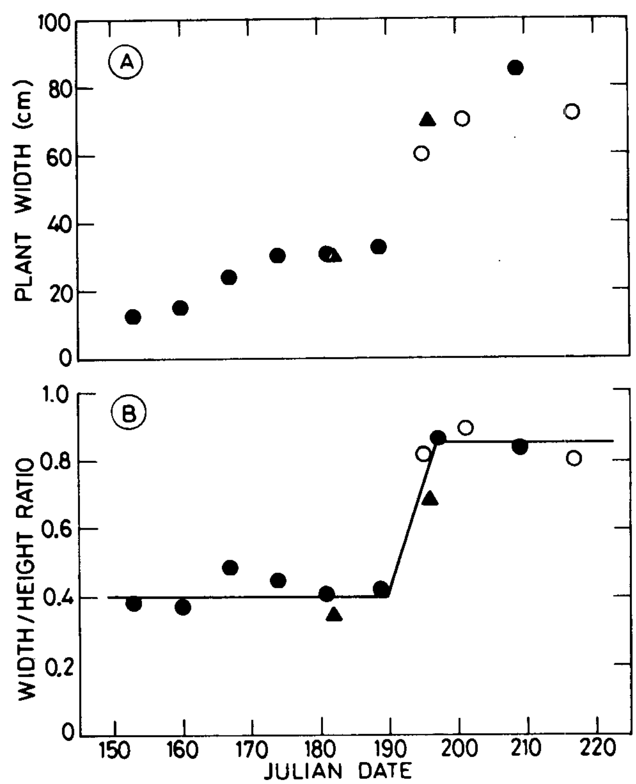

Fig. 9. A. Plant width. B. Ratio of plant width to plant height, Nahal-Oz (1981) under low (○), normal (●), and high (▲) irrigation regimes.

the actual measurements on each day. The agreement between predicted and measured values is usually good, with the exception of two cases. However, this does not prove the validity of the model, mainly because the same set of data was used for calibrating the parameters. It merely indicates the feasibility of using detailed models for predicting radiation penetration, provided that a good characterization of the canopy is available. The model we analyzed was found to be particularly sensitive to leaf angle distribution and plant width.

It has been reported (8, 9, 13, 15) that leaf angle distribution affects radiation interception and photosynthetic efficiency, erectophile canopies being more efficient than planophile ones, especially at medium to high values of LAI. Mann et al. (18) reported that their model is sensitive to leaf angle distribution, but they had no information on this distribution for cotton. In their validation of the model, they assumed that 17% of the leaves were heliotropic, 67% at 10°, and 16% at 30°, but for water stressed plants all the leaves were assumed to droop to 70°. Empirical information on cotton leaf angle distribution is rather scarce. Lang (14) measured leaf elevation angle distribution of unstressed single cotton plants. He found that most of the leaves were between 9° and 54°, with a tendency of more leaves at low elevations in the afternoon. Fukai and Loomis (11) reported that more than half of the leaf area was inclined within the range of 0° and 30°, and leaf inclination increased throughout the day in late June. A pronounced tendency of heliotropism was reported (11, 14), especially before noon. We used in our model runs somewhat different assumptions, but it should be realized that leaf angle distribution is probably modified by cultivar, plant age, moisture stress, and many other factors.

The empirical results, as well as the simulations by the model, indicate that plant width has a significant effect on radiation penetration. Observations of plant width at Nahal-Oz (Fig. 9A) show an abrupt increase in plant width at the beginning of July. This is also true for the ratio of plant width to its height (Fig. 9B). This abrupt change was not correlated with plant height or moisture stress, but we observed that it always occurred when the first bolls began to develop. The weight of the bolls probably causes the fruiting branches to become more horizontal, thus closing the spaces between the rows, although the actual growth of branches was very slow during this period. This phenomenon may also explain some of the deviations from the regression in Fig. 5.

It may be concluded from this study that the use of elaborate models, such as the model of Mann et al. (18), to predict radiation penetration through a canopy can be very useful, provided that reasonably good estimates of the essential parameters are available. The main parameters needed for using the model of Mann et al. (18) are plant height, plant width, LAI, and leaf angle distribution. In case no information is available about these parameters, a good estimate of radiation penetration may be obtained from its regression on plant height. However, plant width may modify this estimate, and it would therefore be useful to have information on this parameter available, and investigate how to include it in the regression.

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