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Visible radiation was measured in sorghum using sensors mounted on a traversing system and having about the same sensitivity to direction and spectrum as does a leaf. As much as 89% more light was transmitted to a sensor when it moved between rows rather than across them. Therefore, measurement across rows is recommended.

Light transmission profiles of sorghum canopies on clear and cloudy days were similar. Differences between transmission values over a diurnal period were less on cloudy than on clear days indicating more uniform light distribution. Visible radiation transmitted through sorghum canopies of .51-m rows as compared to sorghum canopies of .76 and 1.02-m rows or sorghum canopies of .76-m rows as compared to sorghum canopies of 1.02-m rows was less. This would indicate more visible radiation would be available for photosynthesis with narrower row spacings.

Extinction coefficients (K) for canopy layers were calculated and for each layer proceeding downward K decreased. Extinction coefficients of sorghum canopies of different row spacings decreased as row spacing increased. Differences between hourly values of K were less on the cloudy day than on the clear day. For all conditions minimum values of K occurred at solar noon. These results agree with theoretical data.

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Additional index words: Photosynthetically active radiation (PAR), Extinction coefficient, Row spacing, Canopy.

EVIDENCE that solar radiation can be intercepted more efficiently is the generally favorable yield response obtained with narrow row spacings. Colville and Burnside (9) have shown that corn (*Zea mays L.*) planted in .51 and .76 m rows yielded 39 and 28%, respectively, more than corn in 1.02 m rows. Grimes and Musick (11) and Stickler and Weardon (20) showed a grain yield advantage of grain sorghum in .51 m rows over grain sorghum in 1.02 m rows. Direct net radiation studies by Aubertin and Peters (5) indicated that corn plants in .51 m rows absorbed more net radiation than corn plants in 1.02 m rows of equal populations. However, Bowers Hanks, and Stickler (8) concluded from net radiation studies in grain sorghum that the total net radiation absorbed by the plants was only slightly influenced by row spacings.

Because of these discrepancies and because for the most part canopy and solar radiation studies have been theoretical considerations, assuming randomly oriented leaf arrangement, more experimental information is needed concerning culturally arranged plant canopies in relation to absorption of available solar radiation. More specifically, information is needed relative to absorption of solar radiation by canopies in the visible region from 400 to 700 nanometers (nm) which is the photosynthetically active radiation (PAR).

Many difficulties arise in making actual field measurements of radiation under and within plant canopies. The accuracy measurement of light absorbed by plants depends on the similarity between relative plant function and radiation sensors in directional (4, 13, 21) and spectral properties (4, 6, 16). Irregularities of canopy structure are often caused by irregularities of plant spacing. The scale of variation may be large and cannot be covered by a single instrument (4). Several small stationary sensors have been used by some investigators in order to increase spatial sampling, while others prefer a scanning system in which measured radiation flux is monitored as the sensor is moved through the desired portion of the canopy (1, 2, 21). For comparative purposes, several instruments are needed to permit frequent simultaneous measurements of the radiation flux peculiar to the different canopy types under study.

Our objective in the research presented in this paper was to describe the PAR flux under field conditions below and within culturally similar sorghum canopies. The scanning system and radiation sensors with a response similar to that of plant leaf photosynthesis in its directional and spectral properties is also described in this paper.

MATERIALS AND METHODS

Irrigated fields of grain sorghum were established in 1968 at the Nebraska Experiment Station, Mead, Nebraska. Canopies

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Table 1. Hybrid or line, row spacing, population, LAI and sensor height for PAR transmission studies.

Hybrid or line	Sensor height	Row spacing	Plant population	LAI
	m		plants/ha	
RS 626 short	.15	.51	143,700	2.5
RS 626 short	.15	.76	139,392	2.4
RS 626 short	.15	1.02	143,700	2.3
1-814	.15	.46	188,800	3.47
1-814	.15	.61	196,000	3.48
1-814	.15	.92	188,800	3.36
RS 626 tall	1.83 (top)	.76	247,100	0.0
RS 626 tall	1.37	.76	247,100	0.4
RS 626 tall	.91	.76	247,100	1.7
RS 626 tall	.15	.76	247,100	4.5

Table 2. Date, duration, and total PAR for each day's run.

Date in August	Duration (solar time)	Total PAR μeinsteins m^{-2} duration^{-1}
	a.m. p.m.	
12	8:30 - 3:00	4.21×10^7
13	8:30 - 3:00	4.21×10^7
15	10:30 - 3:00	1.57×10^7
16	10:30 - 3:00	3.06×10^7
21	8:00 - 4:00	4.55×10^7

were varied by changing plant type or row spacing. Table 1 gives specific data pertaining to the experiments. RS 626 short and tall were 4-dwarf and 2-dwarf isogenic hybrids, respectively, and 1-814 was an erect leaved line. Plants were fully headed at the time light measurements were made. Measurements were made at half-hour intervals on both clear and cloudy days; however, in the figures only hourly data are presented to eliminate crowding. Duration of instrument operation and amounts of visible radiation for each experimental period are presented in Table 2 and shows that a good comparison between August 12 and 13 could be made because of the same amount of PAR received. Also, the amount of PAR received on August 15 was approximately one-half of the PAR received on August 16. The cloud cover on August 15 was very uniform throughout the experimental period.

Leaf area index (LAI) was determined by the method of Montgomery (18), where LAI = leaf length $\times$ maximum leaf width $\times$ 0.65. The 0.65 factor was determined by J. D. Eastin (personal communication). LAI at different levels in the canopy was determined by placing the plants against a grid corresponding to instrument height and removing with scissors the leaves or leaf parts which fell within the specified stratum. Area on complete leaves was estimated as above and the area of leaf parts was estimated according to whether the part approximated a rectangle (length $\times$ width) or in case of tips a triangle (length $\times$ base width $\times$ 0.5). The areas were summed to give the total leaf area for the desired stratum.

The sensors (Fig. 1) consisted of a Sharp silicon blue cell (SBC-510) with 10 mm of Chance-Pilkington HA3 heat-absorbing glass and a Kodak Wrattan filter CC10M. The Sharp silicon blue cells were matched by checking their spectral response. The filter-cell configuration was potted with clear epoxy in a 1.9-cm black nylon rod adapted to the modified Scripps head (13). An excellent cosine response is obtained by using the Scripps head which is required for most meteorological and agricultural studies.

Field measurements were made using six scanners. Each scanner consisted of two stainless steel slide wires secured above a supporting frame of 2.54-cm dia. conduit. The quantum sensor was mounted on the slide wires and was moved backward or forward by a synchronous motor. A switching terminal was used to control the movement of the six sensors for individual or simultaneous scans. Ninety seconds was required for a complete scan during which time each quantum sensor traversed 3 m. The output of each sensor was independently integrated by electronic integrators with mechanical counter readouts. A stationary-mounted quantum sensor was placed above the canopies for incident light measurement. All sensors were calibrated in full sunlight against a standard quantum sensor. After calibration the instruments were placed in the canopies at the desired height and leveled with a circle bubble level. The construction of the scanner was such that the sensor deviated less than $\pm$ 5° from being level. Because of the cosine response of the sensor this would introduce at maximum an error of 1.5%. Also under a canopy where the light is diffused an error from a sensor not being level would be minimized.

Percent transmission (PT) at various levels was calculated according to the equation:

$$PT = (I_t/I_o) \times 100$$

Mean percent transmission (MPT) an integrated value for the experimental period was calculated according to the equation:

$$MPT = (\Sigma I_t/\Sigma I_o) \times 100$$

I_o is the incident radiation and I_t is the transmitted radiation in the equations.

RESULTS AND DISCUSSION

Quantum Sensor and Spectral Response

The spectral response of the quantum sensor is shown in Fig. 1. The Sharp silicon blue cell has a significantly lower response in the near infrared (700 to 1100 nm) than a silicon solar cell and a higher response in the visible region (400 to 700 nm). This made it possible to eliminate most of the near infrared re-

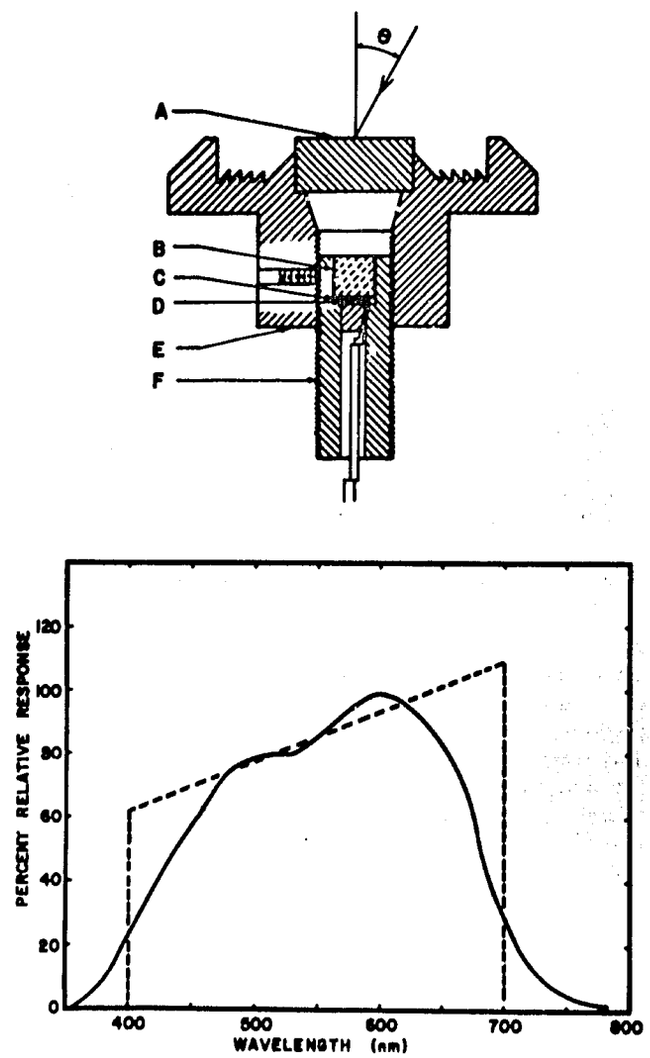

Fig. 1. (Upper) Quantum sensor with cosine-corrected head. A, diffusing plastic; B, heat-absorbing glass; C, Wratten filter; D, silicon blue cell; E, epoxy base, and F, black nylon stem. (Lower) Spectral response of the quantum sensor. Dashed line is the ideal photon response (7).

Table 3. Mean percent transmission (MPT) values of different row spacings as affected by row scanner placement.

Row spacing	Transmission: Scan down row	Transmission: Scan across row	Over-estimate*
m	— mean % —		%
1.02	60	32	89
.76	33	20	69
.51	14	13	2

* Percent overestimate = (MPT down row - MPT across row)/MPT across row × 100.

sponse with appropriate filters. Even though the infrared response of the quantum sensor is low as can be seen in the spectral diagram (Fig. 1), under vegetation the relative amount of infrared increases and the ratio of infrared to visible light increases resulting in an overestimation of available PAR. The error can be as great as 12% under dense vegetation (7), but generally is less because of unobstructed light due to canopy variation and cultural treatments. However, we assumed the error was exponential with LAI and approximated an error, i.e., no error above a canopy and maximum error of 12% if LAI was greater than 3.5. The data were then adjusted with the appropriate error term.

The stability of the filter-cell combination was found to be excellent. The eight quantum sensors used in the field for a 2-month period showed no appreciable change in calibration. The size of the quantum sensor was the biggest disadvantage and limited the studies to plant populations with plant spacings greater than 9.5 cm. Unfortunately, the recently described miniaturized quantum sensors (7, 19) were not available when these studies were initiated.

Scanner Placement

The amount of transmitted PAR received under sorghum canopies was measured at half-hour intervals when the six scanners were located in the center or across north-south rows of different widths. The diurnal transmission curves obtained from the scanners placed in the row are shown in Fig. 2. The peaks reveal the time during which the soil surface between the rows was receiving unobstructed solar radiation. This time period was approximately 3 hours for the 1.02 m row spacing, and approximately 1 hour when the row spacing was reduced to .76 m. No well-defined peak was observed when the row spacing was reduced to .51 m, thus the row effect was essentially eliminated at this spacing. The diurnal transmission curves obtained when the scanners were placed across the rows (Fig. 3) is perhaps more representative of the PAR environment under the sorghum canopies, since the average PAR of the various PAR intensities encountered in crops can be obtained. A comparison of daily means of scanner placement showed that placing the scanner in the row caused an overestimate of the amount of PAR transmitted through sorghum canopies by 89% in 1.02 m rows, 69% in .76 m rows, and only 2.4% in .51 m rows (Table 3) assuming placing the scanners across rows as the acceptable placement method. Essentially a closed canopy existed with the .51 m row spacing and instrument error due to scanner placement was small. Because across-row scanning resulted in averaging PAR in and between rows, the remaining experiments were run with the scanners placed across rows.

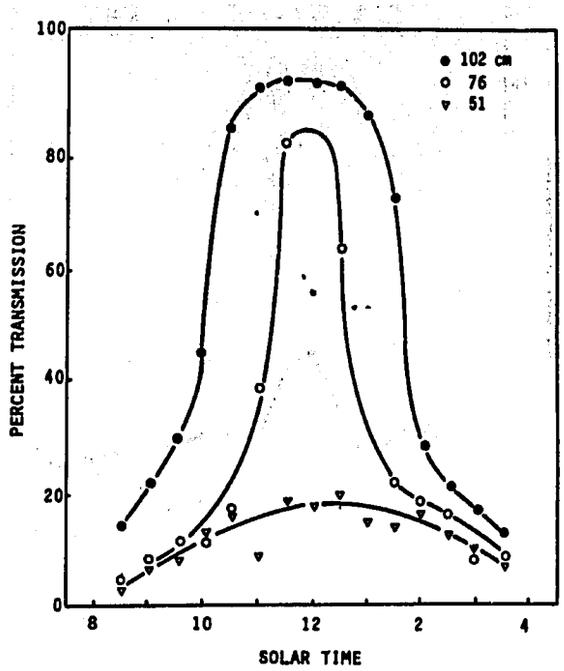

Fig. 2. Percent transmission of PAR through short RS 626 sorghum canopies of different row spacings. Rows were north-south and scanners placed down the center of rows. August 13.

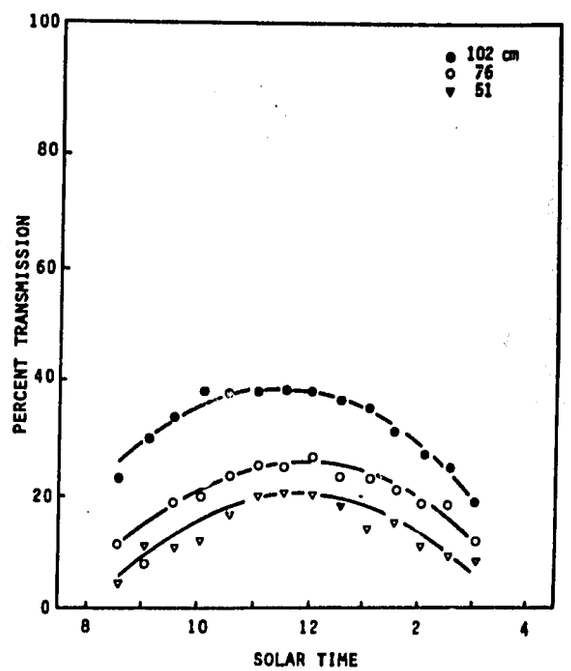

Fig. 3. Percent transmission of PAR through short RS sorghum canopies of different row spacings. Rows were north-south and scanners placed across the rows. August 13.

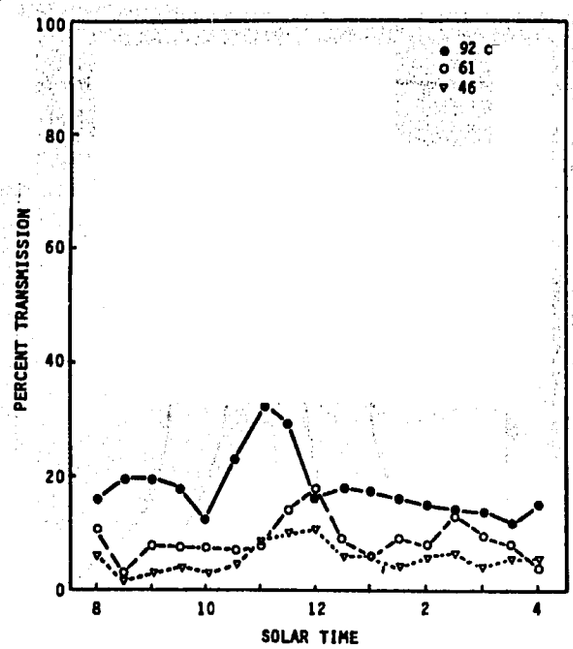

Fig. 4. Percent transmission of PAR through 1-814 sorghum canopies of different row spacings. Rows were east-west and scanners placed across the rows. August 21.

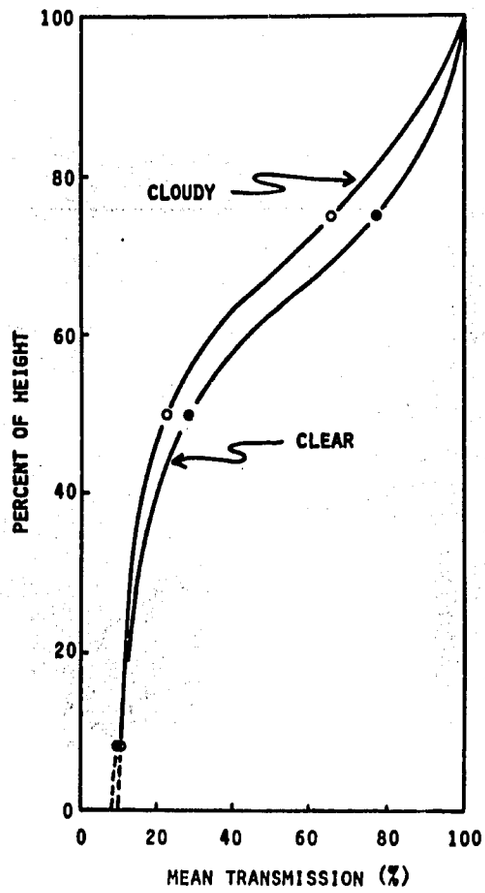

Fig. 5. Mean transmission profiles of PAR through tall RS 626 sorghum in relation to height on a clear (August 16) and cloudy (August 15) day.

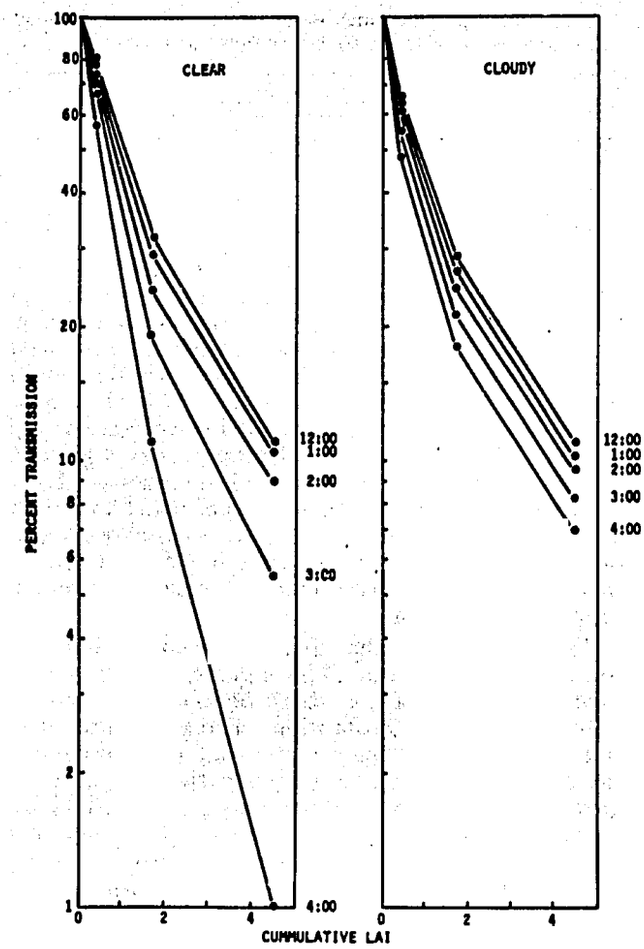

Fig. 6. Percent transmission profiles of PAR through tall RS 626 sorghum in relation to LAI on a clear (August 16) and cloudy (August 15) day. Time indicated is solar time.

Placement of scanners across east-west rows of different row spacings resulted in fluctuating diurnal curves (Fig. 4). Such variation is most likely due to uneven canopy structure, row orientation, and an inadequacy of the length of the scanners. With this type of variation, more frequent sampling throughout the day would be necessary in order to obtain meaningful data.

The aforementioned results readily demonstrate the importance of instrument placement and frequency of sampling that had been emphasized by various researchers (4, 6, 8, 21).

Transmission Characteristics of Sorghum

Examination of the amount of light reaching a given level within a canopy gives some indication of the effectiveness of the canopy for light distribution. Average PAR profiles within the canopy of sorghum for consecutive days, one clear and one cloudy, are shown in Fig. 5. The average profiles for both the days were similar; however, more light penetrated the upper part of the canopy on the clear day than on the cloudy day. The differences in total transmission became less as the measurements proceeded downward due to diffusion of PAR toward the bottom of the canopy. It

was noted that under both conditions 70 to 80% of the PAR had been intercepted by the upper half of the canopy. Due to nonuniform leaf area distribution the upper half included only 38% of the total leaf area. Similar transmission profiles were observed in corn by Loomis et al. (14). They pointed out that the structure of the upper portion of the canopy was very critical for light penetration in the canopy. This would also be true of grain sorghum canopies.

Diurnal light transmission data (curves similar to Fig. 3) at the different canopy depths were fitted to a second order equation; $Y = a + bX + cX^2$, where Y is % transmission and X is time. Correlation coefficients for the data were above 0.90. Points from the smoothed data were then plotted as a function of leaf area index (Fig. 6) since frequently a linear relationship exists (12, 17). On the clear day the maximum amount of PAR which was transmitted through the canopy at solar noon and the diurnal plot of the data was nonlinear. As the sun angle decreased the relationship became more linear, resulting in a large variation in PAR transmission at the various times PAR was measured. Similar results were persented by Allen and Brown (2) in corn studies which were contrary to an earlier report (1). Although Allen et al. (1) fitted light transmission through canopies of corn linearly with a fairly good fit, there was a tendency for the plotted data to be curvilinear.

The PAR transmission data plotted for the cloudy day show a nonlinear relationship similar to that observed for the clear day. The largest difference between PAR transmission for clear and cloudy days was that as the sun angle decreased the relationship for the cloudy day did not become linear. Light diffusion by the clouds caused more uniform lighting throughout the day and this would account for less variation in PAR transmission at the various times PAR was measured.

The amount of PAR which penetrated through canopies of the same population, but in different row spacings, is shown in Fig. 7. The amount of PAR that was transmitted through the canopies decreased as row spacing decreased. On the clear day the relationship was essentially nonlinear, but became more linear as the sun angle decreased, and at a given row spacing the hourly transmission values varied greatly. On

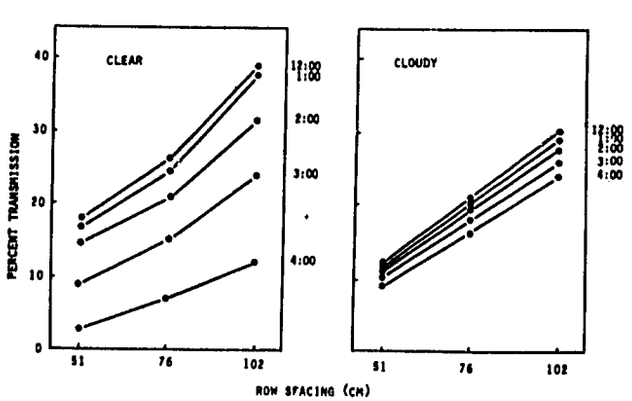

Fig. 7. Percent transmission of PAR through short RS 626 canopies on a clear (August 13) and cloudy (August 15) day. Time indicated is solar time.

Table 4. Extinction coefficients (K) of a grain sorghum canopy as affected by time of day and canopy depth on a clear and cloudy day.

Condition	Solar time	LAI 0.4*	1.4*	2.8*	4.5**
Clear	12:00	.26	.33	.12	.19
	1:00	.28	.34	.14	.21
	2:00	.32	.35	.18	.24
	3:00	.38	.37	.28	.31
	4:00	.53	.37	---	---
Cloudy	12:00	.58	.27	.15	.22
	1:00	.59	.28	.15	.23
	2:00	.58	.28	.16	.23
	3:00	.59	.28	.17	.23
	4:00	.60	.29	.16	.24
	5:00	.63	.29	.16	.24

* LAI of successive canopy layers proceeding downward: 0.4 (1.82 (top) to 1.37 m); 1.4 (1.37 to .91 m); 2.8 (.91 to .15 m). ** Total canopy.

Table 5. Extinction coefficients (K) of grain sorghum canopies as affected by row spacing on a clear and cloudy day.

Condition	Solar time	Row spacing, m .51	.76	1.02
Clear	12:00	.31	.26	.19
	1:00	.31	.27	.20
	2:00	.37	.30	.21
	3:00	.49	.41	.32
Cloudy	12:00	.37	.28	.22
	1:00	.38	.29	.22
	2:00	.38	.29	.22
	3:00	.38	.29	.23
	4:00	.38	.29	.23
	5:00	.37	.30	.23

the cloudy day the relationship between row spacing and percent transmittance was linear and much less variation occurred in the hourly transmission values. Again, this was due to light being diffused by the clouds. Maximum transmission of PAR in both instances occurred when measurements were taken at solar noon. Since less PAR was transmitted through the sorghum in the narrower row spacings, more PAR would be available for use in photosynthesis and would favor increased yields if other conditions such as suitable moisture were adequate.

Extinction coefficients (K) of different canopy layers, total canopy, and row spacings (Tables 4 and 5) were calculated using the equation $I_l = I_o e^{-KL}$ where L is the LAI. Minimum K values occurred at solar noon whether it was clear or cloudy and K increased as the sun angle decreased. The hourly change in K values was much less on the cloudy day. In every instance K decreased as row spacing increased. The extinction coefficients decreased with each successive layer within the canopy on the cloudy day. This may be due to more scattering of the light within the canopy. However, on the clear day K did not decrease until half way down into the canopy and would indicate that the upper layer of the canopy transmitted PAR more effectively on the clear day than on the cloudy day due to light not yet diffused by the canopy.

Anderson (3) concluded, based on a theoretical approach, that K cannot be assumed to be constant in the equation $I_l = I_o e^{-KL}$. Our data concur with her conclusion as indicated by the data in Fig. 6 and 7 and Tables 4 and 5. Therefore, adjustments must be made for nonlinear attenuations of PAR for precise modeling of light within canopies. Although our experiments showed K was not constant, we can possibly explain why use of constant K values has been fairly successful (12, 17). Comparative K's for the cloudy and clear days do not vary greatly for the different

row spacings. With the exception of the top layer, variation of K for the different canopy layers was not large for the clear and cloudy days. Although K for the clear day increased more rapidly as the sun angle decreased in comparison to K for the cloudy day which changed very little, the amount of PAR involved as a percent of the total becomes smaller, and therefore again the use of a constant K probably does not constitute an excessive error.

The considerations of sorghum canopies and PAR presented in this paper are based on field conditions with regard to either row spacing, cloudiness, or distribution. The experimental data presented agree with theoretical data. Precise modeling of light should require changing extinction coefficients for different sorghum canopies and include frequent coefficient adjustment throughout a day depending on time and cloudiness. However, for a given canopy, practically an average daily coefficient probably does not result in excessive error.

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