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Row Spacing Effects on Light Extinction Coefficients of Corn, Sorghum, Soybean, and Sunflower

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ABSTRACT

In many crop models, light intercepted by a canopy (IPAR) is calculated from a Beer's Law equation: IPAR = PAR × [1 − exp(−*k* × LAI)], where *k* is the extinction coefficient, PAR the photosynthetically active radiation, and LAI the leaf area index. The first objective of this study was to investigate the effect of row spacing on *k* for corn (*Zea mays* L.), sorghum [*Sorghum bicolor* (L.) Moench], soybean [*Glycine max* (L.) Merr.], and sunflower (*Helianthus annuus* L.) to provide information for modeling. Data from literature and from an experiment conducted at Temple, TX, were evaluated. The second objective was to investigate effects of time of day and stage of crop development on *k* for different row spacings. Seeds of all four species were sown in rows 0.35, 0.66, or 1.00 m apart. Measurements of canopy light interception were taken near solar noon on two dates before anthesis. At anthesis, extinction coefficients were determined at 0845, 1015, and 1145 h (solar time). The extinction coefficient showed a linear decrease as row spacing increased. For each crop, the effect of row spacing on *k* was described by one linear regression for most data. Stage of crop development and stage of development × row spacing interaction did not significantly affect *k* during the period of measurements. The effect of time of day was significant for all four crops, and the time of day × row spacing interaction was significant for soybean and sunflower. Thus, modeling light interception for different row spacings should account for these effects.

Sowing crops in rows 0.70 to 1.00 m apart at 4 plants m^{-2} or higher, depending on the crop, results in a rectangular pattern (i.e., within-row spacing smaller than row spacing). Plants are more evenly distributed when sown in narrower row spacings, and the efficiency of light interception is improved. An increase in light interception when row spacing is reduced has been reported for corn (Egharevba, 1975), sorghum (Clegg et al., 1974; Muchow et al., 1982), soybean (Mason et al., 1980; Board et al., 1990), and sunflower (Zaffaroni and Schneiter, 1989). Greater light interception often increases yield (Alessi et al., 1977; Karlen and Camp, 1985; Parvez et al., 1989; MacGowan et al., 1991).

The Beer's Law equation estimates interception of solar radiation (IPAR) by a canopy as:

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$$\text{IPAR} = \text{PAR} \times (1 - \exp(-k \times \text{LAI})) \quad [1]$$

where PAR is the photosynthetically active radiation, k is the light extinction coefficient, and LAI is the leaf area index (Thornley, 1976). Many crop models calculate light interception using Eq. [1] without adjusting k for row spacing effects (Spitters and Aerts, 1983; Jones and Kiniry, 1986; Williams et al., 1989; Chapman et al., 1993). However, using an empirical equation the model SORKAM (Rosenthal et al., 1989) predicts greater light interception as row spacing decreases. More complicated approaches calculate light interception from the canopy architecture (usually plant height, plant width, and an empirical coefficient to take into account leaf display), the planting pattern, and the solar angle (Arkin et al., 1978; Hodges and Evans, 1990; Boote and Loomis, 1991). Hence, these models account for row spacing as a result of their construction.

Our objective was to relate k and row spacing in corn, sorghum, soybean, and sunflower with an empirical equation for each crop, so that models using Eq. [1] could account for the effect of row spacing on light interception. Equations were derived from data in literature and from an experiment conducted with all four crops at Temple, TX. This experiment compared k-values for the four species grown in three row spacings at the same location, in the same year, and with the same technique. The extinction coefficients given in literature are mostly measured near solar noon. Thus, the equations calculated from literature in this study accounted for the effect of row spacing on k around midday. Clegg et al. (1974) demonstrated that k for sorghum varies with time of day. Moreover, Zaffaroni and Schneiter (1989) reported a variation in k with crop development. Hence, the second objective of the experiment conducted at Temple, TX, was to investigate effects of time of day and stage of crop development on k for different row spacings. An attempt was made to derive an average daily coefficient from the measurements taken at Temple, TX.

MATERIALS AND METHODS

Field Experiment

The experiment was conducted in 1994 on a Houston Black clay (fine, montmorillonitic, thermic Udic Haplusterts) at the

Abbreviations: IPAR, intercepted PAR; LAI, leaf area index; PAR, photosynthetically active radiation; TPAR, transmitted PAR.

Table 1. Within-row spacings for sunflower, soybean, sorghum, and corn at three row spacings, at Temple, TX, in 1994.

Crop	Within-row spacing, by row spacing			Population density
	0.35 m	0.66 m	1.00 m	
	m			plants m^{-2}
Sunflower	0.402	0.213	0.141	7.1
Soybean	0.125	0.066	0.044	22.8
Sorghum	0.113	0.060	0.040	25.2
Corn	0.386	0.205	0.135	7.4

Grassland Soil and Water Research Laboratory near Temple, TX (31°06 N, 97°21 W). Before planting, 28 kg N ha^{-1} and 70 kg P ha^{-1} were applied as 18-46-0 (N-P-K) and 82 kg N ha^{-1} as urea. Rainfall was adequate to prevent water deficit. Weeds were controlled by hand hoeing. No problems occurred with diseases or insects. Corn (Funks hybrid G4666), sorghum (hybrid Deltapine 1506), sunflower (hybrid Triumph 50), and soybean (Dekalb 'DK 458') seeds were planted 5 cm deep on 7 Apr. 1994 in north–south rows. Plots were seeded to obtain the same population density for all row spacings for one species. Fifty percent emergence occurred on 14 April for sunflower and corn, on 15 April for soybean, and on 18 April for sorghum. Measurements were taken where the stand was even. The plant population densities in these areas were 7.4 plants m^{-2} for corn, 7.1 plants m^{-2} for sunflower, 25.2 plants m^{-2} for sorghum, and 22.8 plants m^{-2} for soybean.

The experimental design was a randomized complete block in a split-plot arrangement with four replicates. Each plot was 18.5 m long and 20.5 m wide. Plot treatments were crop species. Split-plot treatments were row spacings (0.35, 0.66, and 1.00 m). Within-row spacings are reported for each crop in Table 1.

The dates and times of light interception and leaf area measurements are given in Table 2. On 20 June, measurements were taken at three times of the day. Crop growth stage and leaf area on the measurement dates are reported in Table 3. For sunflower, at H1.5 and H4 the head diameters were respectively 1.5 and 4 cm. Fraction of PAR intercepted was measured under clear skies using a 0.80-m Decagon Ceptometer (Decagon Devices, Pullman, WA). Ten measurements were taken above the canopy and 10 below on a 1-m section of row, and then 10 more above the canopy. There were two such readings in each split-plot. Below-canopy measurements were made diagonally across the rows, in order to fit the Ceptometer light bar length (0.8 m) to the row spacing. Thus, the width considered was the row spacing with the row in the middle, except in 0.35-m row spacings, where two rows were considered at the same time. In 1.00-m rows, the results were the means of measurements taken on the left side (0.5 m wide) and on the right side of the row (0.5 m wide). Leaf area was measured on the same section of row and on the same date as light interception measurements. Leaf area was estimated by passing leaves from 20% of the fresh weight of the plants through an area meter (LI-COR, Lincoln, NE, Model 3000). The leaf areas estimated by measuring a subsample and the leaf areas of the whole sample were highly correlated (r^2 = 0.998; slope = 0.996). The light extinction coefficient k was calculated from transmitted (TPAR) and incoming (PAR) data by

$$\mathrm{TPAR/PAR} = \exp(-k \times \mathrm{LAI}) \qquad [2a]$$

Table 2. Dates and times for measurement of light interception and leaf area.

Date (1994)	Time of measurement (solar)
31 May	1145 h
9 June	1030 h
20 June	0845 h
	1015 h
	1145 h

Table 3. Growth stage and leaf area index (LAI) for sunflower, soybean, sorghum, and corn at different measurement dates in 1994 at Temple, TX.

Crop	31 May		9 June		20 June	
	Stage†	LAI	Stage	LAI	Stage	LAI
Sunflower	H1.5	2.34	H4	2.98	Anthesis	2.82
Soybean	R3	1.07	R4	1.41	R5	1.60
Sorghum	5 leaf	2.24	6 leaf	2.75	Bloom	3.09
Corn	6 leaf	2.49	9 leaf	3.72	Silking	3.57

† Growth stages according to Flénet et al., 1994 (sunflower); Fehr and Caviness, 1977 (soybean); Vanderlip, 1972 (sorghum); and Hanway, 1963 (corn).

or

$$k = -\ln(\mathrm{TPAR/PAR})/\mathrm{LAI} \qquad [2b]$$

Assuming that k at 0900 h equals k at 1500 h and that k at 1030 h equals k at 1330 h, daily k-values were weighted for the incoming solar radiation (R):

$$k_w = \frac{2k_{0900h}\,R_{0900h} + 2k_{1030h}\,R_{1030h} + k_{1200h}\,R_{1200h}}{2R_{0900h} + 2R_{1030h} + R_{1200h}} \qquad [3]$$

where the subscripts indicate time of day. Values for R_{0900h}, R_{1030h}, and R_{1200h} used in the calculations were those of a typical summer day (Rosenberg, 1974). Extinction coefficients were measured 15 min earlier than solar radiation (Table 2); it was assumed for calculation that k_{0845h}, k_{1015h}, and k_{1145h} respectively equaled k_{0900h}, k_{1030h}, and k_{1200h}.

Differences among treatments were tested by analysis of variance and were compared using Duncan's multiple range tests at the 0.05 level of significance.

Data from Literature

Data from literature presented in this paper were derived from experiments in which the light extinction coefficient was measured in at least two different row spacings. For studies where the extinction coefficient was not reported (Arkin et al., 1978; Mason et al., 1980; Rosenthal et al., 1985; Board et al., 1990, 1992) or was determined other than by Eq. [1] (Parvez et al., 1989; Westgate et al., unpublished data, 1995), we calculated the k-value from $k = -\ln(\mathrm{TPAR/PAR})/\mathrm{LAI}$. When LAI and TPAR were not reported in tables, data were either digitized (Arkin et al., 1978; Mason et al., 1980; Rosenthal et al., 1985; Parvez et al., 1989; Westgate et al., unpublished data, 1995) or provided by the authors (Board et al., 1990, 1992). In the Muchow et al. (1982) data, sorghum was sown at 267 000 and 600 000 plants ha^{-1}; we used only the k-values for the lower density, more typical of densities in the USA. In Board et al. (1992), 'Centennial' soybean was sown at a late planting date (July) and a seeding rate of 325 000 plants ha^{-1}. In Board et al. (1990), two planting dates (May and July), two plant population densities (220 000 and 325 000 plants ha^{-1}), and two cultivars (Centennial and Forrest) were tested. The extinction coefficients from Board et al. (1990) reported here are the mean values across cultivar, planting date, and plant population density.

RESULTS AND DISCUSSION

Row Spacing Effects on *k*

Extinction coefficients for different crops reported in literature (Monteith, 1969; Varlet-Grancher et al., 1989) were not measured at the same place, nor at the same time; thus, comparison between crops would be confounded with location effects and with measurement techniques. Table 4 reports mean k-values observed at Temple, TX, across the three dates of measurements (31 May, 9 June, and 20

Table 4. The light extinction coefficient *k* for sunflower, soybean, sorghum, and corn as affected by three row spacings; measurements taken around noon at Temple, TX, in 1994.

	k, by row spacing			
Crop	0.35 m	0.66 m	1.00 m	Mean
Sunflower	0.919a†	0.880a	0.623b	0.808A‡
Soybean	0.523a	0.433b	0.323c	0.426B
Sorghum	0.485a	0.461a	0.303b	0.416B
Corn	0.473a	0.398ab	0.336b	0.400B
Mean	0.603A†	0.543B	0.396C	

† Means followed by different letters differ significantly at the 0.05 probability level. Lowercase letters: comparison between row spacings for each crop across the stages of development. Uppercase letters: comparison between row spacings, or between crops, across the other factor.

June at 1145 h) for the three row spacings and the four crops. Mean extinction coefficients at Temple showed no significant difference among corn, sorghum, and soybean, and a mean nearly twice as great for sunflower as for the other crops. As expected according to previous studies (Clegg et al., 1974; Egharevba, 1975; Mason et al., 1980; Zaffaroni and Schneiter, 1989), for all four crops *k*-values significantly decreased with increasing row spacings from 0.35 to 1.00 m, indicating greater light interception efficiency in narrow rows. This improvement in light interception ability of the crops was probably the result of a more even distribution of the plants and hence of the foliage. Row spacing × crop interaction was significant at the 0.10 level ($P = 0.09$). Extinction coefficients decreased by 38% for sorghum and soybean as row spacings increased from 0.35 to 1.00 m, while it decreased by only 32% for sunflower and 29% for corn. Despite that significant interaction, for each row spacing there was little difference in *k* among corn, sorghum, and soybean.

Data from literature and from Temple were plotted against row spacing in Fig. 1a–d. The data from Temple are the means of the values measured on 31 May, 9 June, and 20 June at 1145 h. When fit with a polynomial equation, the quadratic term never differed significantly from zero at the 0.05 level; thus, for the following section a linear function was used for each crop. The regressions between *k* and row spacing were similar for corn, sorghum, and soybean, but very different from that observed for sunflower. If row spacing is set to a conventional value of 0.7 m, the regression equations predict a *k*-value of 0.44

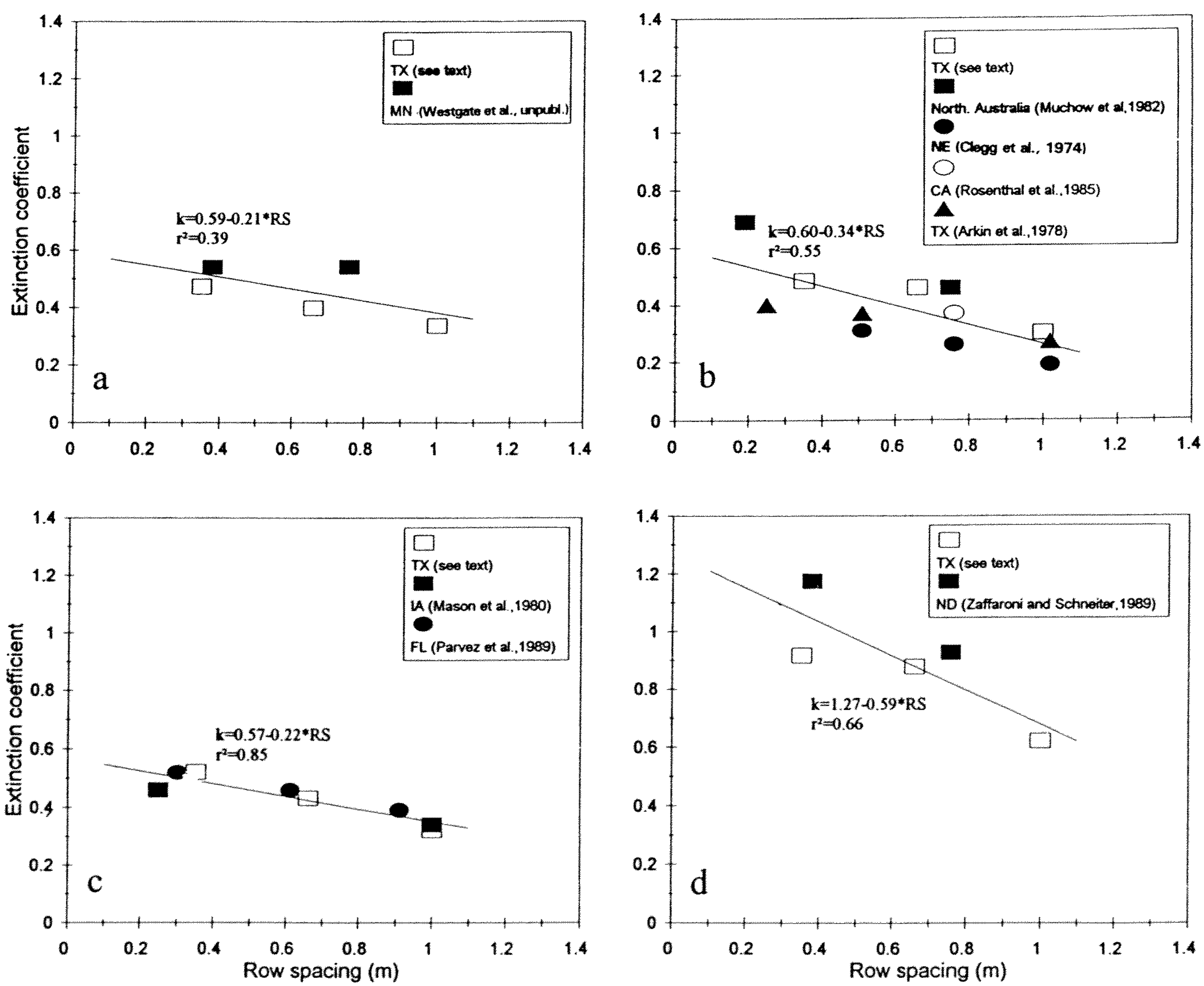

Fig. 1. Effect of row spacing (RS) on the light extinction coefficient *k* measured near solar noon for (a) corn, (b) sorghum, (c) soybean, and (d) sunflower.

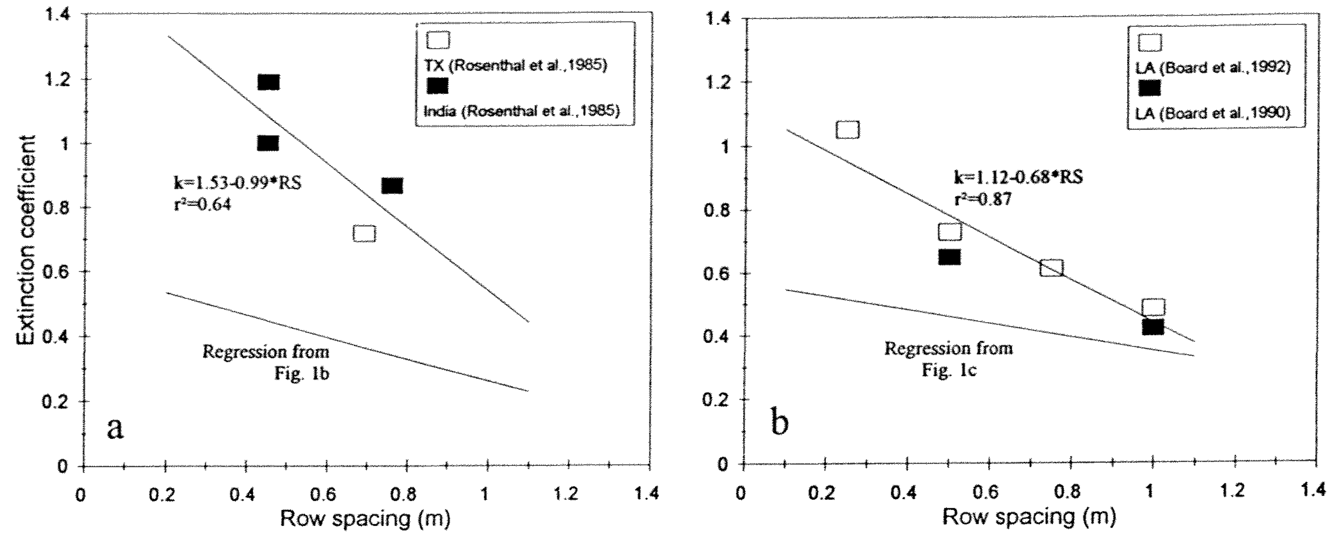

Fig. 2. Effect of row spacing on the light extinction coefficient *k* measured near solar noon: Comparison of (a) sorghum and (b) soybean regressions from Fig. 1 to data measured at locations where *k* was high.

for corn, 0.36 for sorghum, and 0.42 for soybean, but 0.86 for sunflower. Data dissimilar to the extinction coefficients presented in Fig. 1 are shown in Fig. 2a for sorghum and in Fig. 2b for soybean. The lines calculated from the *k*-values in Fig. 1 are included for comparison. Using the equations in Fig. 2, the predicted *k*-values in 0.7-m row spacings are 0.64 for soybean and 0.84 for sorghum.

Most of the *k*-values used in crop modeling are similar to the values calculated by equations in Fig. 1: 0.4 for corn (Muchow et al., 1990), 0.45 for soybean (Kiniry et al., 1992b), and 0.8 (Steer et al., 1993) and 0.9 (Kiniry et al., 1992a) for sunflower. However, other previously used *k*-values in models were 0.6 for soybean (Sinclair, 1986) and 0.65 for corn (Jones and Kiniry, 1986). In SORKAM (Rosenthal et al., 1989), TPAR is calculated from TPAR $= b \times \text{PAR} \times \exp(-k \times \text{LAI})$, where b and k are a function of row spacing, instead of simply TPAR $= \text{PAR} \times \exp(-k \times \text{LAI})$. Thus, the sorghum variations of k with row spacing in Fig. 1b and in SORKAM cannot be directly compared. In Fig. 3, values of TPAR calculated using the equation for sorghum reported in Fig. 1b and calculated using SORKAM are presented for a leaf area index of 3. The two curves are similar, although TPAR estimated with the equation from Fig. 1b is lower than TPAR calculated in SORKAM in narrow row spacings.

The regressions accounted for a great part of the variation observed between *k*-values measured at noon (Fig. 1). However, some differences cannot be explained by row spacing (Fig. 2). The addition of another parameter to row spacing to account for the residual variation would be of great interest. Hiebsch et al. (1990) observed a greater integrated daily light interception in north–south rows than in east–west ones. Canopy height and width, which affect the size of the shadow cast and thus the ability of crops to intercept light (Boote and Loomis, 1991), may also be worth considering. However, *k*-values reported in Fig. 1 and 2 were determined from light interception measured with solar angles close to 90° (near solar noon during summer). When solar angle is 90°, row orientation and canopy height are unlikely to greatly affect the light extinction coefficient. Thus, from the results available in literature, the choice of the most relevant parameter is not clear. Differences in *k*-values are difficult to interpret, because *k* is a coefficient of an empirical equation that models a complex phenomenon. The similar *k*-values and the small difference in the responses of *k* to row spacing (Table 4; Fig. 1) among three crops (corn, sorghum, and soybean) that differ greatly in height, width, and leaf display illustrate that point. More complex models may be more appropriate to simulate light interception when extinction coefficients are different from the values usually observed.

Row Spacing and Time-of-Day Effects on *k*

Light extinction coefficients measured at three different times of day on 20 June are presented in Table 5. Extinction coefficients decreased significantly as solar angle increased during the day. The *k*-value was smallest at noon, the only time when the sun's rays were in the same plane as the rows. Pooling species and row spacing treatments, *k* decreased by 20% every hour and a half. Similar results were reported for sorghum by Clegg et al. (1974). An east–west row orientation would have presumably resulted in less time-of-day effects because in late spring the sun's rays would have been parallel to the rows during the whole day. Time of day × row spacing interaction was not significant ($P = 0.86$). However, when a separate analysis of variance was performed for each crop, time of day × row spacing interaction was significant for sunflower ($P = 0.05$) and for soybean ($P = 0.01$) but not significant for sorghum ($P = 0.55$) or corn ($P = 0.40$). Effect of row spacing on *k* was greater at 0845 h than at 1145 h for soybean and greater at 1145 h than at 0845 h for sunflower. Time of day × crop interaction was significant at the 0.10 level ($P = 0.06$). The *k*-values decreased between 0845 and 1145 h by 44% for soybean and 39% for sorghum, but decreased by only 32% for corn and 31% for sunflower.

The daily extinction coefficient weighted for the incoming solar radiation (daily weighted *k*) was 27% higher than that measured at noon for sunflower, 28% higher for corn,

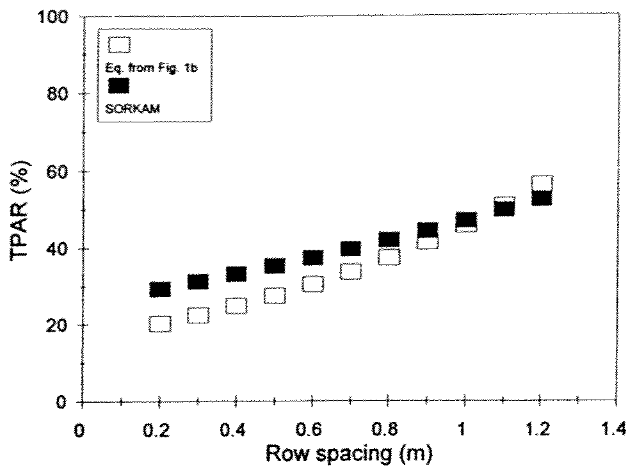

Fig. 3. Effect of row spacing on transmitted photosynthetically active radiation (TPAR) in sorghum: Comparison of the results given by the equation in Fig. 1b and by the equation used in the model SORKAM (leaf area index = 3).

and 30% higher for soybean and sorghum. Thus, extinction coefficients used in crop modeling, based on values measured at noon, can result in large underestimations of daily light interception. The difference between the daily weighted *k* and *k* measured at noon was affected by row spacing. For sunflower, which had a significant time of day × row spacing interaction, this difference ranged from 16% in 0.35-m rows to 52% in 1.00-m rows.

Row Spacing and Crop Stage of Development Effects on *k*

The combined effects of row spacing and stage of development were investigated during the period of rapid growth of the crops. During this period, crop characteristics such as height and width change rapidly and are likely to affect the response of *k* to row spacing. The crop × stage of development interaction was not significant; thus, results are pooled across crops in Table 6. Measurements on 20 June presented here were taken at 1145 h. While *k* differed significantly among sampling dates, it is likely that the 1.25 h earlier sampling time on 9 June was the cause. The 17% increase in *k* for the 9 June sampling is similar to the 20% change in *k* per 1.5 h change discussed above (Table 5). It is concluded that between 6-leaf stage and silking stage in corn, 5-leaf stage and bloom stage in sorghum, R3 stage and R5 stage in soybean, and H1.5 and anthesis in sunflower the stage of plant development had no effect on *k*.

On 31 May, *k* decreased by 43% as row spacing increased from 0.35 to 1.00 m, while it decreased by only 30% on 9 June and 20 June. However, the row spacing × stage of development interaction was not significant (P = 0.52). Thus, the effect of row spacing on *k* did not vary with the stage of crop development during the period of measurements.

CONCLUSION

The light extinction coefficient *k* was greatly affected by row spacing. The decline in *k* between 0.35 and 1.00-m rows ranged from 29 to 38%, depending on the crop. Therefore, crop models would be greatly improved if they accounted for the effect of row spacing on light interception. The decrease in *k* with increasing row spacing for corn, sorghum, soybean, and sunflower was described for each species by one linear regression for most data from different locations (from 30° to 45°N lat, and 15°S lat). Thus, crop models could easily simulate row spacing effects on *k*. However, equations that relate *k* and row spacing did not account for all the variability in *k*-values measured at noon, indicating that other parameters had an effect and that further studies are needed. Row spacing had a greater effect on *k* for soybean and sorghum than for corn and sunflower. The data collected at Temple, TX, indicate that neither *k* nor the row spacing effect on *k* were affected by stage of development during the period of measurement. However, time of day did affect both *k* (for all four crops) and the row spacing effect on *k* (for sunflower and soybean). For all four crops, the daily extinction coefficient weighted by solar radiation was about 30% higher than

Table 5. Effects of row spacing and of the mean time of measurement on the light extinction coefficient *k* for sunflower, soybean, sorghum, and corn, measured at three times of day on 20 June 1994 at Temple, TX.

Crop	Row spacing	*k*, by time of measurement 0845 h	1015 h	1145 h	Weighted mean†
	m				
Sunflower	0.35	1.035	0.980	0.828	0.959
	0.66	1.097	0.990	0.813	0.979
	1.00	1.087	0.905	0.580	0.880
Mean		1.073a‡	0.958b	0.740c	0.939
Soybean	0.35	0.887	0.530	0.460	0.622
	0.66	0.750	0.503	0.433	0.562
	1.00	0.515	0.348	0.320	0.392
Mean		0.718a	0.460b	0.404c	0.525
Sorghum	0.35	0.730	0.585	0.493	0.607
	0.66	0.808	0.610	0.518	0.648
	1.00	0.660	0.453	0.335	0.487
Mean		0.733a	0.549b	0.448c	0.580
Corn	0.35	0.677	0.640	0.460	0.607
	0.66	0.542	0.442	0.408	0.464
	1.00	0.547	0.465	0.325	0.456
Mean		0.589a	0.516b	0.398c	0.509
Overall mean		0.778A‡	0.621B	0.498C	

† Means weighted by incoming solar radiation (see text).
‡ Means followed by different letters differ significantly at the 0.05 probability level. Lowercase letters: comparison between time of measurement for each crop across row spacings. Uppercase letters: comparison between time of measurement across crops and row spacings.

Table 6. Effects of stage of development on the light extinction coefficient *k* measured around noon in 1994 at Temple, TX.

Date†	*k*, by row spacing 0.35 m	0.66 m	1.00 m	Mean
31 May	0.591a‡	0.489b	0.336c	0.472B
9 June	0.660a	0.598a	0.463b	0.572A
20 June	0.560a	0.543a	0.390b	0.498B

† Date indicates stage of development; see Table 3.
‡ Means followed by different letters differ significantly at the 0.05 probability level. Lowercase letters: comparison between row spacings for each stage of development across crops. Uppercase letters: comparison between stages of development across the other factors.

k measured at noon. In sunflower, which had a significant row spacing × time of day interaction, the weighted mean was only 16% higher than the extinction coefficient measured at noon in 0.35-m rows, but 52% higher in 1.00-m rows. Hence, modeling light interception for different row spacings should account for time of day effect and the time of day × row spacing interaction.

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