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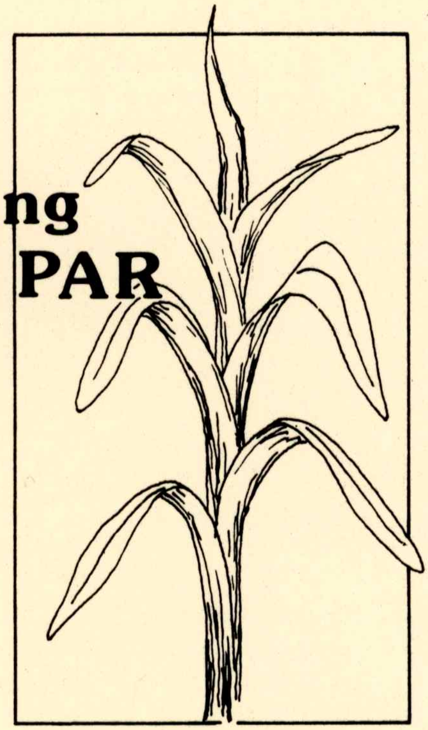
Techniques for Measuring Intercepted and Absorbed PAR in Corn Canopies



by

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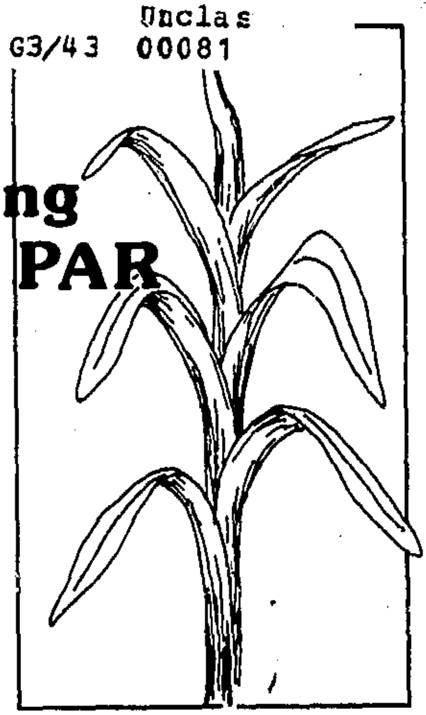

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16. Abstract

The quantity of radiation potentially available for photosynthesis that is captured by the crop is best described as absorbed photosynthetically active radiation (PAR). Absorbed PAR (APAR) is the difference between descending and ascending fluxes. The four components of APAR were measured above and within two planting densities of corn (*Zea mays* L.) and several methods of measuring and estimating APAR were examined. A line quantum sensor that spatially averages the photosynthetic photon flux density provided a rapid and portable method of measuring APAR. The area sampled by an ideal sensor is an integer multiple of the area occupied by a single plant. Thus the length of the ideal sensor is a multiple of the distance between rows and its width is a multiple of the average distance between plants within a row. In practice, the length of a line quantum sensor is determined by the row spacing and several measurements are acquired as the sensor is moved between adjacent plants within a row. PAR reflectance from the soil (Typic Argiaquoll) surface decreased from 10% to less than 1% of the incoming PAR as the canopy cover increased. PAR reflectance from the canopy decreased to less than 3% at maximum vegetative cover. Intercepted PAR (1 - transmitted PAR) generally overestimated absorbed PAR by less than 4% throughout most of the growing season. Thus intercepted PAR appears to be a reasonable estimate of absorbed PAR.

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TECHNIQUES FOR MEASURING INTERCEPTED AND ABSORBED PAR IN CORN CANOPIES

ABSTRACT

The quantity of radiation potentially available for photosynthesis that is captured by the crop is best described as absorbed photosynthetically active radiation (PAR). Absorbed PAR (APAR) is the difference between descending and ascending fluxes. The four components of APAR were measured above and within two planting densities of corn (Zea mays L.) and several methods of measuring and estimating APAR were examined. A line quantum sensor that spatially averages the photosynthetic photon flux density provided a rapid and portable method of measuring APAR. The area sampled by an ideal sensor is an integer multiple of the area occupied by a single plant. Thus the length of the ideal sensor is a multiple of the distance between rows and its width is a multiple of the average distance between plants within a row. In practice, the length of a line quantum sensor is determined by the row spacing and several measurements are acquired as the sensor is moved between adjacent plants within a row. PAR reflectance from the soil (Typic Argiaquoll) surface decreased from 10% to less than 1% of the incoming PAR as the canopy cover increased. PAR reflectance from the canopy decreased to less than 3% at maximum vegetative cover. Intercepted PAR (1 - transmitted PAR) generally overestimated absorbed PAR by less than 4% throughout most of the growing season. Thus intercepted PAR appears to be a reasonable estimate of absorbed PAR.

INTRODUCTION

Solar radiation (SR) is an important energy source for photosynthesis, the process which provides the energy for the growth and production of plants. Because of the importance of SR for photosynthesis, the interaction of SR with plant canopies has been the subject of numerous studies. Only a portion of the incoming SR, however, is utilized by plant canopies in the process of photosynthesis. The spectral limits of photosynthesis are 360 to 760 nm; however, McCree (1972) demonstrated that quantum flux in the 400 to 700 nm waveband was acceptable for defining the response of plants to radiation. Radiation in this waveband is defined as photosynthetically active radiation (PAR) and is measured as photosynthetic photon flux density (PPFD). PPFD is the number of photons in the PAR waveband that are incident on a unit surface in a unit time (Shibles, 1976).

Early studies of the interaction of light with crop canopies examined the probability that a direct beam of light would strike a part of a plant in the canopy and be prevented from continued downward movement through the canopy. When a beam was prevented from further downward movement, it was considered to have been intercepted by the canopy. Methods to determine the probability of direct beam interception, or conversely the frequency of gaps, in the canopy include the use of point quadrats (Warren Wilson, 1960, 1965, 1967), hemispherical photographs taken with a fisheye lens (Anderson, 1971), the number of sunlit tic marks on a wooden bar moved horizontally through the canopy at predetermined increments (Horie, 1966), a laser point quadrat (Vanderbilt et al., 1979) and a mobile sensor mounted on a track and pulled through a canopy (Norman et al., 1971). Under clear sky conditions, at solar elevation angles of greater than 35° (zenith angles <55°), greater than 90% of the total incoming PAR is direct beam PAR (Fuchs et al., 1984). The direct beam penetration into the canopy, however, depends not only on the angle of the direct beam but also on the leaf angle distribution and LAI of the canopy. While measurements of direct beam interception and gap frequency are useful descriptors of the canopy structure, they are unsatisfactory for examining the relationship between crop production and light interaction within the canopy. All of these methods except Norman et al. (1971) inherently neglect the diffuse portion of incoming SR and the SR transmitted through plant parts. Furthermore these methods are all limited in the spatial extent of their usefulness and are tedious and time consuming.

The quantity of energy potentially available for photosynthesis that is captured by a crop canopy is best described as absorbed PAR (APAR). APAR is comprised of four components that represent the descending and ascending fluxes in a crop canopy (Eq. 1).

$$APAR = (PAR_o + RPAR_s) - (TPAR + RPAR_{cs}) \quad (1)$$

The portion of incident PAR (PAR_o) that is transmitted through the canopy to the soil surface (TPAR) will have a portion reflected by the soil ($RPAR_s$) back into the canopy. The PAR measured by a sensor inverted above the canopy will include reflectance of the crop and the soil ($RPAR_{cs}$).

Most studies of SR or PAR interactions with plant canopies have used sensors pointed skyward and positioned above and within the crop canopy (Tanner et al., 1960; Allen et al., 1964; Baker and Musgrave, 1964; Williams et al., 1965; Clegg et al., 1974; Sinclair and Lemon, 1974; Adams and Arkin, 1977; Fakorede and Mock, 1977; Arkin et al., 1978; Sivakumar and Virmani, 1984). This design permits measurement of only incident and transmitted PAR. $RPAR_s$ and $RPAR_{cs}$ were either neglected in these studies or assumed to have relatively small influence on APAR compared to TPAR. Intercepted PAR (IPAR), the total incoming PAR minus the portion transmitted by the canopy (Eq. 2), is often used as an estimate of APAR;

$$IPAR = PAR_o - TPAR \quad . \quad (2)$$

Little information is available on the techniques for sampling transmission or absorption of PAR in crop canopies. No optimum time or solar angle has been defined for measurement of the canopy components of APAR. Direct penetration of light into canopies should be least affected by foliage inclination at a solar elevation of 32.5° (Warren Wilson, 1960; Anderson, 1966). Most previous measurements of light transmitted through canopies have been made near solar noon on cloudless days. Maximum incoming PAR would occur under these conditions and measurement of PAR components at this time is important for determination of canopy interaction with incoming PAR. Ideally the four components of APAR should be measured throughout a day (Asrar et al., 1984). Realistically, the cost of the equipment required to make these measurements may reduce the number of canopies that can be sampled. A measurement system and technique that allows rapid measurement and portability should increase the number of canopies that can be sampled at specific solar angles (i.e., near solar noon). Warren Wilson (1981) suggested that light transmission in row crops be measured over a rectangular area that is centered on one of the plants. The length and width of this area are determined by the respective distances between rows and individual plants within a row.

Our study was conducted to examine several techniques for measuring transmitted and absorbed PAR in corn canopies with a line sensor designed to spatially average the photosynthetic photon flux density. The effects of sensor orientation and surface length on measurements of transmitted PAR and the errors induced by use of intercepted PAR as an estimate of absorbed PAR were examined.

MATERIALS AND METHODS

Agronomic Conditions and Equipment

This study consisted of two experiments conducted at the Purdue University Agronomy Farm (40° 28' N, 87° 00' W). A full season corn (*Zea mays* L.) hybrid ('Adler 30X') was planted in north-south rows with a 76 cm spacing between rows on two dates in 1982 (14 May and 24 June) and 1983 (10 May and 9 June) at two densities (50 and 100 thousand plants/ha). The soil type was Typic Argiaquoll, a dark (10 YR 4/1) silt loam. There were two replicates per treatment. Each plot measured 15.5 by 15.5 m to allow a border sufficient for measurement of TPAR' at low solar elevation angles. Soil analyses were conducted and N, P and K applied to maintain high levels of fertility. Preemergence herbicides were applied for weed control. Tillers were removed from all plants prior to V9 , i.e., 9 leaves emerged (Ritchie and Hanway, 1982).

Photosynthetic photon flux densities (PPFD) were measured under clear sky conditions (cloud cover less than 10% with no clouds within 10° of sun) with a line quantum sensor (LI-COR 191SB). The sensor has a cosine-corrected response to spatially average the incident PPFD over its 100.0 X 1.27-cm rectangular surface. The sensor was modified with the addition of a handle and two bubble levels (one on top and the other on the bottom of sensor). A switch placed within the handle of the sensor allowed the observer to trigger automatic data acquisition by a data logger (Omnidata Polycorder Model 516). Time of each measurement (hour, min, s) was also automatically recorded and used to compute solar zenith and azimuth angles. The sensor was always leveled and positioned such that no shadows from the handle or observer influenced measurements. Care was also taken to minimize possible reflectance from the observer.

Incoming PAR changes during a day due to the changes in solar azimuth and zenith angles. Components of APAR (measured as PPFD) were computed as proportions of the incoming PAR (PAR_o) to compensate for these diurnal variations;

$$TPAR' = (TPAR/PAR_o) \quad , \qquad (3)$$

$$RPAR'_{cs} = (RPAR_{cs}/PAR_o) \quad , \qquad (4)$$

$$RPAR'_s = (RPAR_s/PAR_o) \quad , \qquad (5)$$

$$IPAR' = 1.0 - TPAR' \quad , \tag{6}$$

$$APAR' = 1.0 + RPAR'_s - TPAR' - RPAR'_{cs} \quad . \tag{7}$$

Sensor Orientation-Length Study

TPAR' was measured in 1983 at times of different solar azimuth and zenith angles and crop development stages to examine the effects of sensor length and orientation. Three techniques were used to measure TPAR' in each of the two plant densities. The first included the line sensor positioned perpendicular to the row direction and centered on the row with the full 100-cm (C100) of the sensor surface exposed. The second technique (C76) was identical to the C100 except that it followed the recommendation of Warren Wilson (1981) and exposed a length of sensor equal to the row spacing (76 cm). The third technique positioned the sensor parallel to the row direction with 76 cm (P76) of the sensor surface exposed. Four observations of TPAR' were made for each sensor orientation-length within each planting density.

The P76 technique included the weighted average of seven individual measurements of TPAR made at 12.7-cm increments parallel to the row direction of the canopy. A meter stick was placed perpendicular and between the rows on the soil surface to assure accurate placement of the sensor. The first and last measurements were made with the sensor positioned adjacent to a row of corn and were averaged before being included in computation of TPAR'. The average of three measurements of PAR_o was used to compute TPAR' (Eq. 3).

The C76 and C100 measurements of TPAR consisted of four individual measurements as the sensor was moved at nearly equal increments between plants within a row. TPAR' was computed from the mean of four individual measurements and PAR_o (Eq. 3). PAR_o was measured either above or outside of the canopy within 20 s of the TPAR measurements.

Seasonally Measured Components of APAR

TPAR' was observed at three sites per plot in 1982 at weekly (when possible) intervals throughout the growing season under clear sky conditions at solar noon ± 0.5 hr. TPAR was measured with the previously described C100 technique.

$RPAR_s$ and $RPAR_{cs}$ were measured less frequently during the season than the other components as they were expected to change relatively little. Both of the reflected components were measured at various times (solar azimuth angles) through the day and at times in conjunction with

PAR_o and TPAR'. $RPAR_{cs}$ was measured with the sensor inverted and leveled 35 cm above the mean height of the canopy at two sites per plot. One site centered the sensor over and perpendicular to the crop row. The second site centered the sensor over and perpendicular to mid row. Ten measurements of $RPAR_{cs}$ at each site were averaged and $RPAR'_{cs}$ (Eq. 4) was computed. $RPAR'_s$ is the portion of the PAR_o transmitted through the canopy that is reflected up from the soil surface. Direct measurement of $RPAR'_s$ was not feasible as placement of the line sensor under the canopy at a height of 2.0 cm above the soil surface as used by Asrar et al. (1984) resulted in a large shadow casted on the soil surface within the field of view of the sensor. $RPAR'_s$ was estimated as:

$$RPAR'_s = (RF_s)\ (TPAR') \ , \tag{8}$$

where RF_s is the reflectance factor of bare soil in the PAR wavelengths. RF_s was measured with the sensor inverted and leveled 35 cm above the soil surface at a site of the same soil type adjacent to the plots. RF_s was assumed constant, for the dry soil of this study, regardless of the proportion of direct compared to diffuse radiation incident to the soil surface.

Analysis of Data

In all analyses the components of APAR' were transformed with Eq. (9) to stabilize the variance (Anderson and McLean, 1974, p. 25; Little and Hills, 1978, pp. 159-162),

$$y' = \text{arc sin } y^{\frac{1}{2}} \tag{9}$$

where y is the initial observation and y' is the transformed observation. Mean TPAR' and the time required to complete its measurement were computed for each of the three sensor orientation-exposures for each sample date and plant density. A completely randomized design was utilized in an analysis of variance (SAS, 1979) to identify significant differences in TPAR' observed with the three combinations of orientation and length of the sensor. The data collected in 1982 were combined for the two planting dates, based on development stage of the canopy, to enlarge the data base for some analyses. Components of APAR' were not dependent on planting date compared to plant density when the data were analyzed for similar stages of canopy development.

Mean TPAR' $RPAR'_s$ and $RPAR'_{cs}$ were computed and examined for seasonal fluctuations. The effect of plant density on TPAR' and $RPAR'_{cs}$ was examined. APAR' was computed (Eq. 7) for those dates when data were available for all PAR components at solar noon. The errors between APAR' computed with Eq. (7) and APAR' estimated with IPAR' (Eq. 6) were examined.

RESULTS AND DISCUSSION

Sensor Orientation-Length Study

The TPAR' observed with the three sensor orientation-length (OL) techniques displayed similar trends over the growing season (Table 1). TPAR' decreased as LAI increased for both plant densities and increased slightly with leaf senescence (R5). More light was transmitted through the canopies with 50,000 plants/ha than those with 100,000 plants /ha for all sensor OL techniques. Significant differences (α=0.01) were detected for TPAR' observed with the three sensor OL techniques for three of the nine observations (Table 2). Examination of TPAR' values in Table 1 revealed that the P76 sensor system was most likely responsible for the detected differences. A t-test analysis of TPAR' observed with the C76 and C100 sensors detected significant (α=0.01) differences between these systems only on 17 June (50,000 plants/ha) and 17 Sept. (100,000 plants/ha).

The lack of significant effects of sensor OL, compared to plant density, on TPAR' was expected as all three of the sensor OL techniques used in this study closely approximated the ideal area of measurement suggested by Warren Wilson (1981). While Warren Wilson's (1981) recommendations are valid, they are more critical in canopies with well defined (hedge-like) row structures (e.g., widely spaced rows of soybeans) than in canopies with overlapping leaves and poorly defined row structures (e.g. corn). A hedge-like canopy could be expected to develop a well defined boundary between primarily direct and diffuse light due to shadows cast by the canopy. The use of a single point sensor to measure TPAR in a canopy with a well defined row structure is an extreme example of an erroneous measurement. In this example, a point sensor may be completely sunlit and overestimate TPAR or completely shadowed and underestimate TPAR. Spatial sampling of the area occupied by plants within a canopy is essential.

The time required to complete an observation was significantly affected by sensor orientation (Tables 2 and 3). This result was partially due to the greater number of individual measurements that comprised a P76 observation compared to C76 or C100. The greater number of individual measurements in a P76 observation (twice that of C76 or C100) was not solely responsible for the disparity in measurement times. A portion of the observation time was devoted to accurate placement of the sensor at the predefined increments between the canopy rows. A meter stick was used to aid the placement of the sensor. The C76 and

Table 1. Summary of 1983 sensor orientation-length observations of transmitted PAR.

		solar angle		Plant Density (plants/ha)							
				50,000				100,000			
date	development stage	elv.	azimuth	LAI	C76	P76	C100	LAI	C76	P76	C100
		- degrees -			-- TPAR' (%) --				-- TPAR' (%) --		
17 June	V6	65	128	0.33	84.6	78.0	79.8	0.78	75.3	61.8	73.8
25 June	V8	49	101	1.57	35.0	35.2	38.8	2.25	16.9	19.4	18.7
6 July	V12	47	100	2.67	12.7	13.8	9.3	4.97	2.8	2.6	2.3
6 July	V12	72	197	2.67	17.5	28.1	23.5	4.97	9.8	10.6	15.9
19 July	R1	48	104	3.04	9.4	7.4	10.2	6.05	3.4	1.6	2.5
21 July	R1	69	198	3.04	17.8	26.7	18.4	6.05	2.6	5.8	3.5
8 Aug.	R3	57	130	2.84	6.7	13.4	9.1	5.63	1.3	2.7	1.3
29 Aug.	R5	58	160	2.56	19.6	10.7	20.8	4.74	4.4	5.1	5.4
17 Sept.	R5	56	186	2.85	29.2	26.0	30.9	4.07	10.6	13.6	17.7

Table 2. Summary of F tests from the 1983 study of the effects of sensor orientation-length (OL) and plant density on transmitted PAR and the time required for measurement.

	F values			
	TPAR'		time	
date	sensor OL	plant density	sensor OL	plant density
17 June	78.0**	255.8**†	965.4**	2.5
25 June	2.8	342.1**	476.0**	2.9
6 July	3.7	232.6**	902.5**	4.6*
6 July	1.2	9.4**	528.3**	2.6
19 July	5.5*	138.5**	886.9**	5.8*
21 July	26.6**	596.4**	565.8**	0.0
8 Aug.	14.5**	188.7**	408.1**	3.3
29 Aug.	5.2*	116.0**†	1823.4**	2.4
17 Sept.	4.6*	108.7**	252.5**	2.4

*, ** indicate significance at the 0.05 and 0.01 levels of probability, respectively.

† data displayed a significant sensor OL X planting density interaction

Table 3. Summary of time required to measure transmitted PAR in the 1983 sensor orientation-length study.

date	development stage	Sensor Orientation-Length: 50,000 plants/ha C76	P76	C100	100,000 plants/ha C76	P76	C100
		---seconds---					
17 June	V6	12	64	12	12	69	13
25 June	V8	14	57	17	12	58	12
6 July	V12	20	91	24	23	83	21
6 July	V12	20	78	20	23	82	21
19 July	R1	18	81	18	17	72	18
21 July	R1	18	71	18	19	70	19
8 Aug.	R3	18	75	18	17	67	16
29 Aug.	R5	17	82	19	16	82	16
17 Sept.	R5	26	80	24	30	78	31

C100 sensor systems were much simpler as they only required that the sensor be centered on the row and incremented at equally spaced intervals between plants within the row. Adams and Arkin (1977) used 21 individual measurements per parallel observation. While more measurements might improve the accuracy of the P76 technique, the time required to complete an observation would undoubtedly increase.

Seasonal Changes in Observed TPAR'

TPAR' observed at solar noon for corn planted on 14 May 1982 decreased rapidly from a maximum possible 100% at planting to less than 20% at 65 days after planting (DAP) (Fig. 1). Late in the growing season as the canopies senesced (stage R5) TPAR' increased. Significantly (α=0.01) more radiation was transmitted through canopies with 50,000 plants/ha compared to canopies with 100,000 plants/ha on 15 of 22 observation dates. These 15 dates included 8 different stages of crop development that ranged from five leaves (V5) to full dent (R5). TPAR' observed for the corn canopies planted on 24 June 1982 displayed similar trends to that observed for the canopies planted on 14 May.

Seasonal Changes in Observed RF_s and $RPAR'_{cs}$

Reflectance of a relatively smooth soil surface varies little with illumination angle (Kollenkark et al., 1982), although moisture can significantly reduce its reflectance (Stoner et al., 1980). RF_s of dry soil was 9.3 ± 0.5% (n=270) and moist soil RF_s was 5.0 ± 1.0% (n=65). $RPAR_s$ of dry soil ranged from 10% of PAR_o when no canopy was present to less than 1.0% of PAR_o under a full canopy cover.

Significant differences in $RPAR'_{cs}$ of the two plant densities were detected (Table 4); however, the differences were less than 1% of the incident PAR. $RPAR'_{cs}$ was lowest after full canopy vegetative development (from stages V14 to R2) and before canopy senescence (R5). $RPAR'_{cs}$ varied between the two plant densities by less than 0.2% during this interval. The reflectance of green corn leaves in the PAR waveband was less than that of the dry bare soil of this study. $RPAR'_s$ and $RPAR'_{cs}$ were equal at planting (by definition), but as the vegetation obscured the soil, the reflectance of the composite scene (soil and vegetation) decreased. Throughout most of the growing season $RPAR'_{cs}$ was less than 5%.

Comparison of IPAR' with APAR'

The differences between IPAR' and APAR' were computed for six observation dates that included a wide range in crop development (Table 5). The errors between predicted (IPAR') and observed APAR' were less

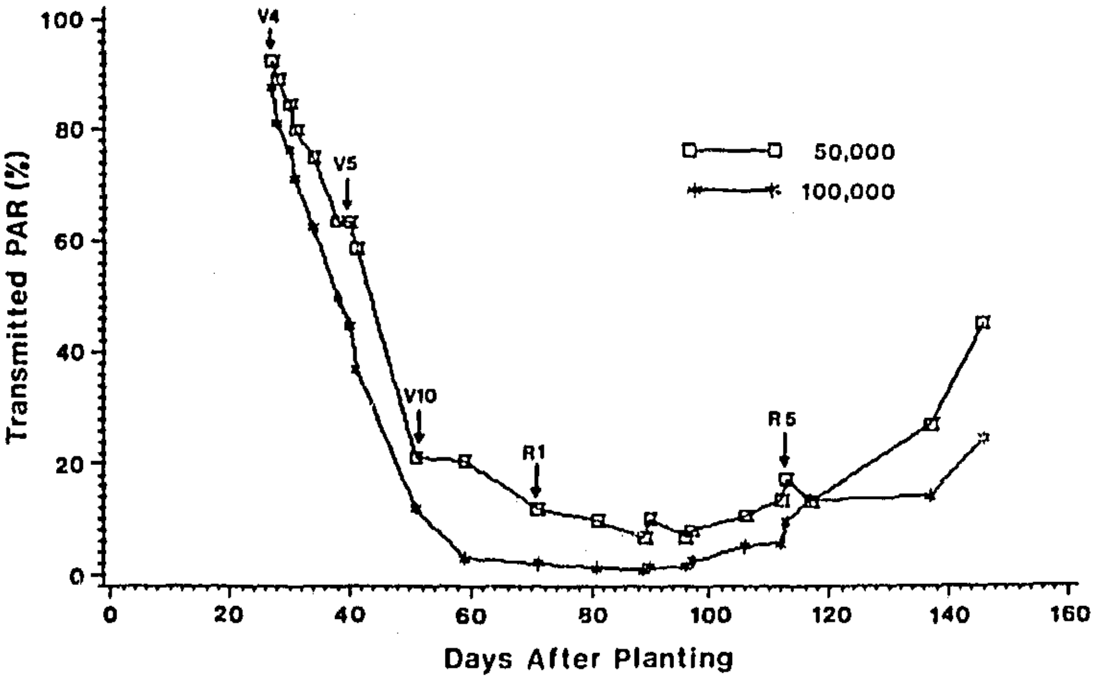

Figure 1. Transmitted PAR plotted as a function of days after planting for observations of the 14 May 1982 planting of corn. Standard deviations of TPAR' were less than the width of the symbols used to represent the mean values.

Table 4. Mean $RPAR'_{cs}$ at solar noon for the 50,000 and 100,000 plants/ha densities of corn. A t-test was used to identify significant differences.

development stage	plant density (plants/ha) 50,000	100,000	t-value
	----------%----------		
V6	6.2	5.2	7.4**
V8	4.1	3.4	70.2**
V14	2.9	3.0	-3.2**
V15	2.7	2.7	-0.5
V15	2.8	2.6	7.3**
VT	3.2	3.1	4.7**
R2	3.2	3.4	-10.1**
R5	5.9	6.4	-10.1**

** indicates significance at the 0.01 level of probability.

Table 5. Comparison of observed APAR' (Eq. 7) with APAR' estimated with IPAR' (Eq. 6).

development stage	RPAR'$_s$	RPAR'$_{cs}$	TPAR'	IPAR'	APAR'	e†
	%					
			50,000 plants/ha			
V6	7.4	6.2	79.9	20.1	21.3	-1.2
V8	5.4	4.1	58.6	41.4	42.7	-1.3
V14	1.9	2.9	20.5	79.5	78.5	1.0
VT	1.1	3.2	11.7	88.3	86.2	2.1
R2	0.9	3.2	9.8	90.2	87.9	2.3
R5	1.2	5.9	13.3	86.7	82.0	4.7
			100,000 plants/ha			
V6	6.6	5.2	71.2	28.8	30.2	-1.4
V8	3.4	3.5	36.9	63.1	63.0	0.1
V14	0.3	3.0	3.0	97.0	94.3	2.7
VT	0.2	3.1	2.2	97.8	94.9	2.9
R2	0.1	3.4	1.3	98.7	95.4	3.3
R5	0.5	6.4	5.7	94.3	88.4	5.9

† e = (IPAR' - APAR')

than 3.5% until the dent (R5) stage. TPAR' increased slightly during the dent stage as leaves senesced and the leaf angle distribution changed (became more vertical). The increased reflectance from senesced leaves, and the increase in bare soil reflectance due to changes in the leaf angle distribution, contributed to decreased APAR'. The increase in TPAR' (decrease in IPAR'), due to leaf senescence and changes in the leaf angle distribution, did not match the increase in $RPAR'_{CS}$ and resulted in the relatively large errors between predicted and observed APAR' at R5. Generally, when the vegetation of the canopy is predominately green, IPAR' is a satisfactory estimate of APAR'.

SUMMARY AND CONCLUSIONS

Sensor orientation and length (OL) can be important for the accurate measurement of the components of APAR and are dependent on the row and plant spacing of the canopy. When a spatial average of PPFD is measured and a canopy displays overlapping leaves between rows, as in this study, OL effects on observed TPAR' are reduced. Measurement of TPAR with a line quantum sensor should include horizontal placement of the sensor perpendicular to and centered on a canopy row. The area sampled should be an integer multiple of the area occupied by a single plant. Individual measurements with a sensor, which has a length determined by the row spacing, should be made at equal intervals between plants within a row. PAR reflected from the soil ($RPAR_S$) and canopy ($RPAR_{CS}$) varied with crop development and planting density of the canopy (amount of leaf area present). The effect of reflected (diffuse) PAR, however, was minor when compared with the effect of transmitted (direct and diffuse) PAR on absorbed PAR. Intercepted PAR (computed as the portion of PAR_O transmitted through the canopy to the soil surface) was a reasonable estimate of absorbed PAR and required fewer measurements.

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