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ESTIMATING COTTON LEAF AREA INDEX NONDESTRUCTIVELY WITH A LIGHT SENSOR

H. Tewolde,* K. R. Sistani, D. E. Rowe, A. Adeli, and T. Tsegaye

Abstract

AccuPAR, which is a relatively new instrument for estimating leaf area index (LAI) by measuring light interception, has wide distribution but only limited independent evaluation of its accuracy. The objective of this study was to evaluate the accuracy of AccuPAR for estimating LAI of cotton (*Gossypium hirsutum* L.) planted on different row spacings. Cotton LAI was measured nondestructively with AccuPAR and destructively by taking plant samples three to four times during each growing season in 2002 and 2003 on research conducted at three locations in Mississippi, USA. The results suggested that meter accuracy was affected by differences between row spacing and the length of the light-sensing segment of the meter. Supplemental tests showed that meter accuracy improved with meter placement, which eliminated length differences and with near solar noon measurements, which minimized row-to-row shading overlap. We conclude that the meter can more accurately estimate row crop LAI when the under-canopy placement of the meter and the time of measurement are selected so that the light-sensing segment of the meter captures shading of an entire row cross-section and that row-to-row shading overlap is eliminated or minimized.

Leaf area index (LAI) is a key input in the analysis of crop growth and productivity, water use, and in the management of weeds and other pests. Direct LAI measurement, however, is labor-intensive, slow, and intrusive. It can be highly variable and imprecise if adequate plant samples are not taken. Because of the difficulty, a number of different ways of measuring LAI have been tested and used. One of the easier and less expensive methods for measuring LAI is a measurement that relies on specific leaf area (SLA) measurement. This involves taking the dry weight of small leaf discs with known area from the bulk plant samples and calculating SLA as A_d/W_d where A_d = area and W_d = dry weight of all leaf discs. The leaf area of the bulk leaves is calculated as $A_b = \text{SLA} \times W_b$ where A_b = area and W_b = dry weight of bulk leaves (Marani and Levi, 1973) assuming SLA based on leaf discs represents SLA of the bulk leaves. This method is prone to errors because SLA based on small leaf discs does not always represent bulk leaf SLA. Tewolde et al. (2002) used this method for measuring peanut (*Arachis hypogaea* L.) LAI by determining SLA based on all leaves from a branch chosen to represent the bulk leaves. Their results show the effectiveness of the method in measuring relatively small LAI differences among treatments.

Leaf area estimation based on leaf dimensions such as length and width has also been used. Hoyt and Bradfield (1962), Winter and Ohlrogge (1973), Krishnamurthy et al. (1974), and Bange et al. (2000), for example, estimated individual leaf area of corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), and sunflower (*Helianthus annuus* L.) leaves from measurements of leaf length, width, and conversion factors. This method can be nondestructive because the leaf dimensions necessary for estimating leaf area can be measured on intact leaves. However, it can be as labor intensive as measuring LAI by destructive methods.

Availability of leaf area machines made the task of measuring leaf area less tedious, but they are not the solution to the tediousness and labor-intensiveness of measuring LAI. Leaf area continued to be measured the hard-way by cutting whole plants, separating all the leaves from the plants, and passing the leaves through the leaf area machines in the laboratory (Bednarz et al., 2000; Pettigrew, 2002; Fritschi et al., 2003).

Once leaf area on individual plant samples is measured or estimated using the different approaches, LAI is calculated by extrapolation from individual plants to plant stand. Many researchers in the past sampled a few plants per plot, measured or estimated the leaf area of these plants, determined plant stand, and then calculated LAI as the product of leaf area per plant and plant stand per unit ground area (Stoner et al., 1976; Jost and Cothren, 2001; Aparicio et al., 2002; Reta-Sánchez and Fowler, 2002). This approach is subject to errors because the two to five plant samples selected for leaf area measurement usually are insufficient and also the selection is subject to bias.

The availability of nondestructive instrumentation in relatively recent years has allowed the measurement of LAI indirectly without any destructive sampling. There have been at least three commercial instruments for indirect measurement of LAI: Li-cor's LAI-2000 Plant Canopy Analyzer, Decagon Devices' AccuPAR, and Delta T Devices' SunScan. Of these three meters, the LAI-2000 has been tested and used relatively extensively (Welles and Norman, 1991; Hicks and Lascano, 1995; Wilhelm et al., 2000; Ganguli et al., 2000; de Jesus et al., 2001; Malone et al., 2002; Holshouser and Whittaker, 2002). With the exception of a test that compared the LAI-2000 against the other two newer machines (Wilhelm et al., 2000), the accuracy of the AccuPAR and SunScan meters, which may be as suitable as the LAI-2000, has not been sufficiently evaluated for use

H. Tewolde, D.E. Rowe, and A. Adeli, USDA-ARS, 810 Highway 12 East, Mississippi State, MS 39762; K.R. Sistani, USDA-ARS, 230 Bennett LN, Bowling Green, KY 42104; and T. Tsegaye, Alabama A&M Univ., P.O. Box 1208, Normal, AL 35762. Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. Received 28 Apr. 2004. *Corresponding author (htewolde@ars.usda.gov).

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Abbreviations: LAI, leaf area index; PAR, photosynthetically active radiation; SLA, specific leaf area; UAN, urea–ammonium nitrate solution.

in row crops. A listing of users of the AccuPAR by the manufacturer, Decagon Devices, shows that the meter has a relatively large worldwide users (Decagon Devices, 2003), but only little published research information exists on its ability to measure LAI on agronomic crops. The objective of this study was to evaluate the accuracy of the AccuPAR for estimating LAI of cotton planted on different row spacings.

Materials and Methods

The AccuPAR meter model PAR-80 was evaluated in 2002 and 2003 in a multi-location research project designed to evaluate poultry litter as an alternative cotton fertilizer. The research was conducted on commercial farms at Macon, Cruger, and Coffeeville, MS. At each location, 10 treatments that received litter between 0 and 6.7 Mg ha^{-1} with or without supplemental N as urea–ammonium nitrate solution (UAN) at 34 or 67 kg N ha^{-1} were compared in a randomized complete block design with three or four blocks. Plots were eight 91-m long and 0.76-m wide rows at Macon, four 119-m long and 1.02-m wide rows at Cruger, and eight 73-m long and 0.97-m wide rows at Coffeeville. Cultivars planted included Sure-Grow SG 501 BR at Macon and Coffeeville, Stoneville BXN 49B at Cruger in 2002, and Stoneville ST 4892 BR at Cruger in 2003.

AccuPAR, which is manufactured by Decagon Devices (Pullman, WA), was used to measure canopy light (400–700 nm) interception and calculate LAI three to four times between 1 and 2 wk before flowering and defoliation at each location. The meter as described by the manufacturer consists of a light-sensing segment and a microcontroller (Fig. 1). The light-sensing segment, which will be referred to as the sensor bar hereafter, is 0.8 m long with 80 independent photodiodes spaced 0.01 m apart (Decagon Devices, 2001). The interception of photosynthetically active radiation (PAR) by the cotton canopy was measured by taking one reading above the canopy followed by another reading under the canopy. Five sets of such readings were taken per plot. Each of the five readings was taken on row segments typical for the plot. The reading below the canopy was taken by placing the sensor bar approximately perpendicular to one of the center two rows in each plot with one end (Photodiode 80) of the bar aligned on top of the first row-center (Fig. 1). The other end (Photodiode 1) of the sensor bar reached as far out from the first row-center across the furrow to the second row-center. All readings were taken by programming the meter to measure and record PAR interception and LAI on five (2002) or seven (2003) equally spaced segments of the sensor bar. According to the instruction manual, taking segmented readings is particularly useful when rows have not fully closed. The average of these five or seven readings was used for analysis. The latitude, longitude, time, and date were entered into the meter so that the zenith angle of the sun is automatically calculated by the meter. The meter uses the sun zenith angle and PAR interception to calculate LAI using inversion equations (Decagon Devices, 2001). Nearly all measurements were made on days with clear sky conditions. Because the meter estimates LAI based on light measured above and below the canopy, extra care was taken to ensure that sky conditions did not change before completing the below-canopy light readings once above-canopy light reading was logged.

Destructive LAI was measured based on whole plant samples collected from the center two rows of each plot at the same time nondestructive LAI measurements were made with the AccuPAR. The samples were taken from 0.61-m row at

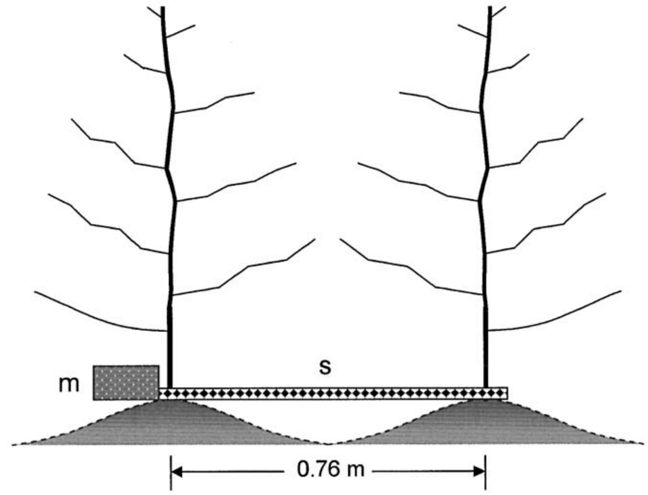

Fig. 1. Schematic illustration of the under-canopy placement of the AccuPAR during measurement of cotton LAI. m = microcontroller; s = light sensor bar.

each location making the sampling area to be 0.46 m^2 at Macon, 0.59 m^2 at Coffeeville, and 0.62 m^2 at Cruger. Specific leaf area was determined in the laboratory by detaching all leaves from one of the six to eight plant samples per plot and further partitioning the leaves into petioles and leaf blades. Surface area of the leaf blades was then measured with Li-Cor LI-3000 Portable Area Meter, which is equipped with LI-3050A Transparent Belt Conveyer Accessory (Li-Cor, Lincoln, NE). The leaf blades and petioles were dried to constant weight in a forced-air oven at 80°C and weighed. Average SLA (cm^2 g^{-1}) was determined as the area of the leaf blades divided by their dry weight. Whole leaves from the remainder five to seven plants were separated from the stem, dried to constant weight in a forced-air oven at 80°C, and weighed. The area of the bulk leaves (A_b) was calculated as A_b = SLA $\times$ W_b $\times$ W_f, where W_b = dry weight of bulk leaves and W_f = ratio of leaf blade dry weight to whole leaf (petioles plus blades) dry weight. Leaf area index was then calculated as A_b divided by the ground area the plant samples occupied.

Plant height was measured as the distance between the cotyledonary node and the last node on the main stem of plants used for destructive LAI measurement. Chlorophyll index was measured on the last fully expanded leaf of five plants per plot with Minolta's SPAD meter.

Regression and correlation analysis was used to test the accuracy of the AccuPAR for estimating LAI. Leaf area index measured with the meter was regressed on LAI measured destructively within each location separately and tested for departure from a 1:1 relationship. In addition to regression and correlation analysis, LAI measured by the two methods averaged across treatments within each location and date was subjected to paired t test to statistically assess the departure of LAI measured by the AccuPAR from LAI measured destructively.

Two supplementary evaluations as a follow-up to this study were conducted in 2003 and 2004 on cotton planted on rows spaced 0.97 m and received high or no N fertilization. The first supplementary evaluation was made on 2 Sept. 2003 to quantify the contribution of nonfoliar plant parts to the LAI estimated by the AccuPAR. The second supplementary evaluation was made on 13 July 2004 to test whether different ways of under-canopy placement of the sensor bar improve the accuracy of the meter. In both evaluations, measurements with

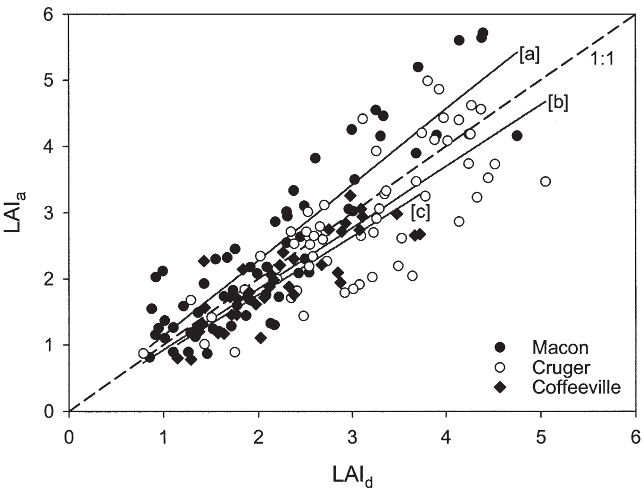

Fig. 2. Regression of cotton LAI estimated nondestructively with AccuPAR (LAI_a) on LAI measured destructively (LAI_d) during the 2002 and 2003 cotton growing seasons at Macon and Cruger and during the 2002 growing season at Coffeeville, MS. The fitted lines were constrained to pass through the origin. Each data point is an average of three or four replications. The respective slopes and r^2 values for the fitted lines are (a) 1.14 and 0.81 for Macon, (b) 0.93** and 0.66 for Cruger, (c) 0.88** and 0.77 for Coffeeville, and 0.98 (NS) and 0.69 for the line (not shown) fitted to all data points. (** = slopes significantly departed from 1.0 at $P < 0.01$; NS = departure of slope from 1.0 not significant at $P < 0.05$).**

the AccuPAR were made in the same way as in the main study on the middle two of four rows replicated three times. In 2004, additional AccuPAR readings were taken by placing the sensor bar parallel or diagonal to the rows at the same time the across-row meter readings were taken. Because the sensor bar was shorter (0.80 m) than the row spacing (0.97 m), it was necessary to take two diagonal readings on each half of the space between the two rows (for a total of four readings) to capture canopy shading equivalent to an entire row cross-section. A total of five equally spaced readings were taken when the sensor bar was placed parallel to the rows. After the AccuPAR measurements, leaf blades from all plants on the 0.77-m^2 two-row section in 2003 and 0.97-m^2 in 2004 were hand-removed, their area measured, and LAI determined as described earlier. Plant height and chlorophyll index measurements were also recorded.

Results

Regression analysis of the data after combining across dates within each location showed that the meter under- or overestimated destructively measured LAI. Regression of LAI estimated with the AccuPAR on destructively measured LAI by forcing the regression line to pass through the origin showed that the fitted lines significantly ($P < 0.05$) departed from the 1:1 line at all three locations (Fig. 2). The slopes of all fitted lines which were 1.14 for Macon, 0.93 for Cruger, and 0.88 for Coffeeville data were significantly ($P < 0.05$) different from 1.0. These slopes and the position of the fitted lines relative to the 1:1 line show that the meter overestimated LAI at Macon but underestimated it at both Cruger and Coffeeville.

When the data were averaged across treatments within each date and location, the meter under- or overestimated the destructively measured LAI by 15% or less in 9 of the total 16 measurements (Table 1). The meter was most accurate at Cruger where three of the six AccuPAR LAI measurements were not significantly different from the destructively measured LAI. The meter underestimated destructively measured LAI on all dates at Coffeeville but none of the underestimations exceeded 17%. The meter was most inconsistent at Macon where the row spacing was 0.76 m compared with 1.02 m at Cruger and 0.97 m at Coffeeville. The meter under- or overestimated LAI by >20% in 5 of the total 16 measurements from all locations and dates.

The results of the test to evaluate contributions by

Table 1. Leaf area index of cotton measured destructively (LAI_d) or nondestructively with the AccuPAR (LAI_a), plant height, and chlorophyll index averaged across 10 poultry litter and conventional N fertilizer treatments at three research sites in Mississippi in 2002 and 2003.

Location (row spacing)	Date	LAI_d	LAI_a	Over- or underestimation†	Plant height	Chlorophyll index	Time measurement started	Zenith angle at start of measurement
m				%	cm		h	
Macon (0.76)	22 July 2002	3.50	4.10	17.1*	82.9	40.6	0834	59.6
	14 Aug. 2002	2.88	3.69	28.3***	83.6	41.5	0837	61.6
	3 Sept. 2002	1.65	2.24	35.9**	86.0	42.5	0822	67.1
	9 July 2003	1.56	1.34	−14.1**	49.4	33.7	0924	48.3
	6 Aug. 2003	1.73	1.98	14.6***	57.6	35.2	1205	21.8
	21 Aug. 2003	1.65	1.27	−22.8**	54.2	34.4	0950	47.3
Cruger (1.02)	25 July 2002	4.11	3.84	−6.5NS‡	94.4	48.4	0954	43.2
	9 Aug. 2002	3.78	4.23	11.9**	97.8	47.9	1015	42.3
	27 Aug. 2002	2.50	2.58	3.4NS	96.5	45.6	0923	55.2
	3 July 2003	2.51	2.40	−4.3NS	76.4	39.4	1333	12.1
	23 July 2003	3.35	2.55	−23.9***	82.3	47.9	1031	37.2
	15 Aug. 2003	2.36	1.65	−30.1**	84.6	46.2	1039	38.5
Coffeeville (0.97)	10 July 2002	1.76	1.46	−17.3*	52.3	42.5	1004	39.9
	31 July 2002	2.71	2.40	−11.2*	74.9	45.0	0912	53.9
	22 Aug. 2002	2.56	2.46	−4.1NS	76.6	45.9	0915	55.8
	10 Sept. 2002	1.90	1.62	−15.2*	77.7	48.0	0918	57.7
Avg.		2.53	2.49	−1.7	76.7	42.8	0956	46.3

* Significant at $P < 0.05$ level.
** Significant at $P < 0.01$ level.
*** Significant at $P < 0.001$ level.
† Comparison between LAI_d and LAI_a within each date using a paired t test.
‡ NS = not significant at $P < 0.05$.

Table 2. LAI measured with AccuPAR (LAI_a) before and after hand-defoliation compared with LAI measured destructively (LAI_d). Only leaf blades were removed from the defoliated plants. Each value is an average of three replications. The average zenith angle when these measurements were taken was 37.6.

Applied N	LAI_a Non defoliated	LAI_a Defoliated	LAI_d	LAI over- or underestimation†	Plant height	Chlorophyll index	Specific leaf area
kg ha^{-1}				%	m		cm^2 g^{-1}
0	2.12	0.35	2.46	−13.7NS‡	0.87	30.7	155.4
118	5.36	0.57	4.33	23.7§	1.34	38.0	208.4
LSD(0.05)	1.80	NS	1.20		0.13	3.78	3.27
CV, %	13.7	37.3	10.1		3.4	3.1	0.5

† Comparison between nondefoliated LAI_a and LAI_d within each N rate using a paired *t* test.
‡ NS = not significant at $P < 0.10$.
§ Significant at $P < 0.10$.

nonfoliar plant parts showed that the AccuPAR overestimated LAI of the taller and greener 94-d old cotton plants when the measurements were taken before defoliation at an average zenith angle of 37.6 (Table 2). Measurements with the meter after removing all leaf blades showed that nonfoliar plant parts such as stems, petioles, and reproductive parts can contribute to the overestimation of LAI by as much as 14%. Average LAI of the defoliated treatment as measured by the AccuPAR was 0.35 for plants that did not receive N and 0.57 for plants that received 118 kg ha^{-1} UAN-N. Malone et al. (2002) showed LAI reading of up to 0.96 due to nonfoliar plant parts in hand-defoliated soybean when measured with the LAI-2000 Plant Canopy Analyzer (Li-Cor, Lincoln, NE), which also estimates LAI indirectly. Our results also indicated that the AccuPAR underestimated LAI of the shorter and chlorotic plants and overestimated LAI of the much taller and greener plants (Table 2). This indicates LAI differences between N-deficient and N-sufficient treatments can be exaggerated when measured with the AccuPAR.

The test to evaluate the effect of meter placement and time of measurement showed that the AccuPAR accurately estimated LAI of cotton planted on 0.97-m when the measurements were made around solar noon (<15 zenith angle) and by placing the sensor bar diagonal to the rows (Table 3). Placement of the sensor bar parallel to the rows also resulted in a relatively accurate LAI estimates. The meter underestimated LAI when the sensor bar, which was shorter than the row spacing, was placed perpendicular to the rows. The underestimation was more severe in the N-deficient, chlorotic, and short plants than in the N-sufficient, greener, and taller plants.

Discussion

The accuracy of the AccuPAR in estimating LAI of cotton seems to depend on several factors including row spacing, plant height, time of measurement, influence of nonfoliar plant parts, and leaf chlorophyll concentration associated with the stage of plant growth. The owner's manual offers little or no guidelines on how these factors affect the accuracy of the meter. Without such guidelines, it is likely that row crop LAI will be under- or overestimated when measured with the AccuPAR. Wilhelm et al. (2000), for example, reported that the AccuPAR and two other similar meters underestimated LAI of corn planted on 0.76 m rows but offered no explanation why such underestimation occurred.

Row spacing, plant height, and time of measurement in row crops determine the magnitude of row-to-row shading overlap, a condition that can lead to the overestimation of AccuPAR-measured LAI. Depending on the row spacing and plant height, row-to-row shading overlap is largest at sunrise or sunset and is at its minimum when the sun is directly overhead. Thus, LAI is likely to be overestimated when measured with the AccuPAR at times substantially earlier or later than when the sun is directly overhead (zenith angle of zero).

The overestimation of LAI at Macon but not at the other two locations in 2002 may be attributed, in part,

Table 3. Comparison of destructively measured LAI against LAI estimated with the AccuPAR with its light sensor bar placed under the canopy across, diagonally, or parallel to the rows. The AccuPAR measurements were made near midday when the average zenith angle was <15. Each number is an average of three replications.

Relative N	LAI measurement method†	LAI	LAI under- or overestimation	Plant height	Chlorophyll index
			%	m	
High	destructive	4.08	0.0	1.02	38.4
	across row	3.49	−14.5‡		
	diagonal	3.97	−2.5NS§		
	parallel	3.63	−11.0NS		
Low	destructive	1.61	0.0	0.72	28.6
	across row	1.14	−29.1**		
	diagonal	1.65	2.6NS		
	parallel	1.61	−0.1NS		

** Under- or overestimation of LAI measured with the AccuPAR relative to destructively measured LAI significant at $P < 0.01$ level.
† LAI measurement method: Destructive = leaf area measured by passing all leaf blades through leaf area machine; across row, diagonal, parallel = LAI estimated with AccuPAR by placing the sensor bar perpendicular to rows as in the main study, diagonally, or parallel to the rows, respectively.
‡ Under- or overestimation of LAI measured with the AccuPAR relative to destructively measured LAI significant at $P < 0.10$ level.
§ NS = under- or overestimation not significant at $P < 0.10$.

to a greater zenith angle, the row spacing being narrower than the length of the AccuPAR's light sensor bar, and relatively tall plants. All measurements at Macon in 2002 were made earlier in the morning than at the other two locations (Table 1). The row spacing at Macon was 0.76 m compared with 0.97 m at Coffeeville and 1.02 m at Cruger. The sesnor bar of the AccuPAR is 0.80 m long, which is slightly longer than the row width at Macon (Fig. 1). Thus, measurements of light interception and LAI with the meter, at Macon, were made on a full row cross-section plus some shading from adjacent rows. The rows at Coffeeville and Cruger, on the other hand, were spaced substantially wider than the length of the sensor bar and, therefore, the bar did not cover the entire cross-section of the row at these two locations. Using a meter with the sensor bar shorter than the row width, before canopy closure in particular, could lead to LAI estimation that departs from the actual when the placement of the bar is across the rows as described in our procedure.

Plant height can also contribute to over- or underestimation of LAI by increasing the magnitude of row-to-row shading overlap when measurements are not made near solar noon. Relatively tall plants may be one reason of the better LAI estimation by the AccuPAR at Cruger than at Coffeeville in 2002 while the row spacings at the two locations were comparable. On average, plants at Cruger in 2002 grew as tall as 0.98 m when measured from Node 0 to the last node (Table 1). The average plant height at Coffeeville during the same year was only 0.77 m. We suspect the taller plants at Cruger in 2002, relative to plants at Coffeeville in the same year, may have resulted in a greater overlap of shading and this overlap may have offset underestimation of LAI due to row spacing wider than the length of the sensor bar. The underestimation of LAI at Coffeeville may be due to a combination of relatively short plants and the sensor bar being shorter than the row width.

Shading due to nonfoliar plant parts and variation in PAR interception due to differences in leaf chlorophyll concentration are other factors that can result in over- or underestimation of LAI when measured with the meter. The PAR interception by a canopy that is composed of lighter green leaves is expected to be less than the interception by a canopy that is composed of darker green leaves although both canopies may have the same LAI. The owner's manual does not address the effect of leaf greenness on the accuracy of the meter, but we believe the greater underestimation on the last measurement date at Macon and Cruger in 2003 and at Coffeeville in 2002 may be related to loss of chlorophyll concentration in the majority of the leaves. The chlorophyll index data (Table 1) do not seem to support this because those measurements were made on the youngest top single leaves. These leaves toward the end of the season were by far greener than the bulk of the leaves on a plant.

The meter does not distinguish light interception due to stems, branches, petioles, bolls, and other nonfoliar plant parts from light intercepted by leaf blades. Our test (Table 2) and that of Malone et al. (2002), using hand-defoliated plant canopy, demonstrated that the contribution of nonfoliar plant parts to the AccuPAR-measured LAI can be substantial. Obviously, the influence of the nonfoliar plant parts on the LAI readings is in the absence of any leaf. Whether the nonfoliar plant components have the same influence on LAI of nondefoliated plants, however, is not obvious from our study or that of Malone et al. (2002).

Suggestions to Minimize Over- or Underestimation of Leaf Area Index Measured by the AccuPAR

The owner's manual adequately describes how to operate the meter but offers very little guidelines with regard to measurement procedures such as meter placement under the canopy, time of measurement, and potential errors. Placement of the meter under the canopy and choice of time of measurement are two important factors that can be controlled by the user for effective use of the meter to estimate LAI of row crops.

We suggest the placement of the meter under the canopy be in such a way that the sensor bar captures shading of an entire row cross-section with no additional shading from neighboring rows. This can be achieved by choosing meters with the light sensor bar to be equal to the row spacing and by placing the bar across the row from one row-center to the next row-center. When the length of the sensor bar exceeds the row spacing, the most reasonable method is to place the bar across the row diagonally so that the first photodiode is aligned on one row-center and the last photodiode is aligned on the next row-center. It is also possible to program the meter so that readings can be taken from part of the sensor bar that equals the row spacing. If the sensor bar is shorter than the row spacing, we suggest a measurement scheme different than placing the bar across the row. For example, taking several measurements at different distances from the row with the sensor bar placed parallel to the row may be a better way to measure LAI than placing it across the row. If it is necessary to place the sensor bar across the rows, one possible but more time-consuming option is to place the bar from row center to mid-row on each side of the row, adjusting the diagonal placement as necessary.

In addition to choosing a suitable under-canopy positioning of the meter, choosing time of day during which no row-to-row shading overlap occurs should minimize overestimation of row crop LAI measured by the AccuPAR. Whether there is shading overlap can easily be determined by observing whether shading from one row falls beyond the target row. Depending on the plant height, shading overlaps are largest early in the morning and decrease until the overlaps disappear when the sun is directly overhead, but increases again as the zenith angle increases toward late afternoon.

Considering the difficulty of measuring LAI destructively and the variability due to inadequate sampling that usually is associated with destructive methods, the AccuPAR can become a useful research instrument for estimating LAI if proper measurement procedures can be established and a description of these procedures included in the owner's manual. We believe awareness of potential sources of error and incorporation of our suggestions in devising LAI measurement schemes with the AccuPAR can substantially improve the accuracy of the meter.

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