LARS Technical Report 062984
NASA-Johnson Space Center
Contract No. NAS9-16528

(E85-10041 NASA-CR-171822) SPECTRAL ESTIMATORS OF ABSORBED PHOTOSYNTHETICALLY ACTIVE RADIATION IN CORN CANOPIES (Purdue Univ.) 20 p HC A02/MF A01 CSCL 02C

N85-16242

Unclas
G3/43 00041

Spectral Estimators of Absorbed Photosynthetically Active Radiation in Corn Canopies

by

K. P. Gallo
C. S. T. Daughtry
M.E. Bauer

Laboratory for Applications of Remote Sensing

West Lafayette, Indiana 47906
USA

PURDUE, touching tomorrow today

Star Information Form

1. Report No	2. Government Accession No	3. Recipient's Catalog No

4. Title and Subtitle	5. Report Date
Spectral Estimators of Absorbed Photosynthetically Active Radiation in Corn Canopies	6/29/84
	6. Performing Organization Code
7. Author(s) K.P. Gallo, C.S.T. Daughtry, and M.E. Bauer	8. Performing Organization Report No 062984
9. Performing Organization Name and Address Laboratory for Applications of Remote Sensing Purdue University 1291 Cumberland Ave. West Lafayette, IN 47906-1399	10. Work Unit No. 11. Contract or Grant No. NAS9-16528
12. Sponsoring Agency Name and Address NASA Johnson Space Center Houston, TX 77058	13. Type of Report and Period Covered Technical 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract Most models of crop growth and yield require an estimate of canopy leaf area index or absorption of radiation. Direct measurement of LAI or light absorption can be tedious and time consuming. The objective of this study was to develop relationships between photosynthetically active radiation (PAR) absorbed by corn (Zea mays L.) canopies and the spectral reflectance of the canopies. Absorption of PAR was measured near solar noon in corn canopies planted in a field experiment conducted at the Purdue University Agronomy Farm, West Lafayette, IN, on a Typic Argiaquol at densities of 50,000 and 100,000 plants/ha. Reflectance factor data were acquired with a Landsat MSS band radiometer. From planting to silking, the three spectrally predicted vegetation indices examined were associated with more than 95% of the variability in absorbed PAR. The relationships developed between absorbed PAR and the three indices were evaluated with reflectance factor data acquired from corn canopies planted in 1979 through 1982 that excluded those canopies from which the equations were developed. Treatments included in these data were 2 hybrids, 4 planting densities (25, 50, 75, and 100 thousand plants/ha), 3 soil types (Typic Argiaquol, Udollic Ochraqualf, and Aeric Ochraqualf) and several planting dates. Seasonal cumulations of measured LAI and each of the three indices were associated with greater than 50% of the variation in final grain yields from the test years. Seasonal cumulations of daily absorbed PAR were associated with up to 73% of the variation in final grain yields. Absorbed PAR, cumulated through the growing season, is a better indicator of yield than cumulated leaf area index. Absorbed PAR may be estimated reliably from spectral reflectance data of crop canopies.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Remote Sensing, (Zea mays L.), Light Interception, Crop Models	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA - JSC

NAS9-16528
LARS 062984

SPECTRAL ESTIMATORS OF ABSORBED PHOTOSYNTHETICALLY ACTIVE RADIATION IN CORN CANOPIES

K.P. Gallo
Formerly Graduate Research Associate, LARS
Now Assistant Professor, Agronomy, Cornell University

C.S.T. Daughtry
Senior Research Agronomist, LARS

M.E. Bauer
Formerly Senior Research Agronomist, LARS
Now Director, Remote Sensing Laboratory,
University of Minnesota

Laboratory for Applications of Remote Sensing
Purdue University
West Lafayette, IN 47906-1399, U.S.A.

June 1984

LARS Technical Report 062984

SPECTRAL ESTIMATORS OF ABSORBED PHOTOSYNTHETICALLY ACTIVE RADIATION IN CORN CANOPIES

ABSTRACT

Most models of crop growth and yield require an estimate of canopy leaf area index or absorption of radiation; however, direct measurement of LAI or light absorption can be tedious and time consuming. The objective of this study was to develop relationships between photosynthetically active radiation (PAR) absorbed by corn (Zea mays L.) canopies and the spectral reflectance of the canopies. Absorption of PAR was measured near solar noon in corn canopies planted in a field experiment conducted at the Purdue University Agronomy Farm, West Lafayette, IN, on a Typic Argiaquol at densities of 50,000 and 100,000 plants/ha. Reflectance factor data were acquired with a Landsat MSS band radiometer. From planting to silking, the three spectrally predicted vegetation indices examined (ratio of red to near infrared reflectance, normalized difference, and greenness) were associated with more than 95% of the variability in absorbed PAR. The relationships developed between absorbed PAR and the three indices were evaluated with reflectance factor data acquired from corn canopies planted in 1979 through 1982 that excluded those canopies from which the equations were developed. Treatments included in these data were two hybrids, four planting densities (25, 50, 75, and 100 thousand plants/ha), three soil types (Typic Argiaquol, Udollic Ochraqualf, and Aeric Ochraqualf) and several planting dates. Seasonal cumulations of measured LAI and each of the three indices were associated with greater than 50% of the variation in final grain yields from the test years. Seasonal cumulations of daily absorbed PAR were associated with up to 73% of the variation in final grain yields. Absorbed PAR, cumulated through the growing season, is a better indicator of yield than cumulated leaf area index. Absorbed PAR may be estimated reliably from spectral reflectance data of crop canopies.

INTRODUCTION

Remote sensing from aerospace platforms can provide information about crops and soils which could be useful for modeling crop development and production. The feasibility of utilizing multispectral data from satellites to identify and measure crop area has been demonstrated (MacDonald and Hall, 1980), however, relatively little research has been conducted to develop methods of incorporating multispectral data into models that provide information about crop condition and yield. Most models of crop growth and final yield (Arkin et al., 1975; Coelho and Dale, 1980; Stapper and Arkin, 1979; Steven et al., 1983) require an estimate of a canopy's green leaf area index (LAI), absorption of solar radiation (SR) or, more appropriately, absorption of photosynthetically active radiation (PAR). Measurements of LAI or absorbed PAR are tedious and time consuming for small research plots (Daughtry and Hollinger, 1984) and impossible to obtain over large areas.

Numerous spectrally predicted vegetation indices have been proposed and used to make quantitative estimates of LAI, phytomass, and percent soil cover (Asrar et al., 1984; Perry and Lautenschlager, 1984; Steven et al., 1983). These vegetation indices exploit differences in reflectance patterns of green vegetation and other materials within a scene. The simplest index is the ratio (Eq. 1) of near infrared (800 to 1100 nm) and red (600 to 700 nm) reflectances.

$$RATIO = IR/red \qquad (1)$$

A closely related vegetation index is the normalized difference (Eq. 2) which is the difference in the infrared and red reflectances divided by the sum of the two reflectances.

$$ND = (IR - red) / (IR + red) \qquad (2)$$

The third vegetation index is the greenness index (GI) which is a linear transformation that accentuates the presence of green vegetation (Rice et al., 1980). The greenness index (GI) is computed as:

$$GI = -0.4894\ RF_1 - 0.6125\ RF_2 + 0.1729\ RF_3 + 0.5954\ RF_4 \qquad (3)$$

where RF_1 through RF_4 are the reflectance factors in bands 500 to 600, 600 to 700, 700 to 800 and 800 to 1100 nm, respectively. While GI is sensitive to green vegetation it is relatively insensitive to changes in the amount of shaded area within row crop canopies that result from the diurnal changes in solar azimuth and zenith angles (Kollenkark et al., 1982).

Leaf area index and the proportion of solar radiation intercepted by corn canopies may be estimated with GI (Daughtry et al., 1983). Similarly, LAI and the proportion of PAR absorbed by wheat can be estimated with ND or GI (Asrar et al., 1984; Hatfield et al., 1984).

The seasonal duration of leaf area is frequently a more important indicator of grain yields than maximum LAI produced. Correlations of grain yields with spectral or agronomic data acquired on a single date during the growing season of a crop may be spurious and must be used with caution (Daughtry et al., 1983). Vegetation indices accumulated for various portions of the growing season have been found to be associated with significant proportions of the variance in grain yields of wheat (Pinter et al., 1981; Tucker et al., 1980), corn (Daughtry et al., 1983; Walburg et al., 1982) and sugar beets (Steven et al., 1983).

The daily interpolation of spectral transformations, or spectrally predicted agronomic variables, through a crop's growing season have been related to grain yield. The normalized difference computed with the 650 to 700 nm (red) and 780 to 820 nm (near IR) wavebands and interpolated for portions of the growing season was associated with 64% of the variance in grain yield of wheat (Tucker et al., 1980).

Daily dry matter production may be described as a function of the total incident solar radiation, the proportion of solar radiation intercepted, and the efficiency of conversion of solar energy to phytomass (Steven et al., 1983). When the proportion of intercepted SR was estimated with multispectral data and the predicted daily dry matter production was cumulated over the growing season, Steven et al. (1983) were able to predict dry matter of sugar beets at harvest within 6%.

Our study was conducted to develop relationships between absorbed PAR and several vegetation indices and to examine the relationship between grain yield and spectrally estimated absorbed PAR.

MATERIALS AND METHODS

This study consisted of experiments conducted over four years at the Purdue University Agronomy Farm, West Lafayette, IN (40^{o} 28' N, 87^{o} 00' W). Two replicates of an adapted corn (Zea mays L.) hybrid were planted on several dates at several plant densities (Table 1). The two soil types in Experiments I and II had distinctly different spectral reflectance characteristics in the red and near IR wavebands. The corn was planted in north-south rows with 76 cm spacing between rows. Soil analyses were conducted and N, P, and K applied to maintain high levels of fertility. Preemergence herbicides were applied for weed control.

Daily meteorological data were recorded at the cooperative National Weather Service station (West Lafayette 6NW) that was within 200 m to the east of the plots. Incoming solar radiation was measured with an Eppley Precision Spectral Pyranometer and was recorded as total MJ m^{-2} day^{-1}. The photosynthetically active portion of the daily SR was assumed to be 0.5 (McCree, 1966; Szeicz, 1974). Daily incident photosynthetic photon flux density (PPFD) was computed as:

$$PPFD = 0.5\ (SR)\ 4.6\times 10^{-6} \qquad (4)$$

where SR is the daily incident solar radiation and 4.6×10^{-6} is the conversion factor (moles/J) determined by McCree (1972).

Canopy Characterization

Agronomic variables were usually measured at weekly intervals and included leaf area index and development stage (Ritchie and Hanway, 1982). Green leaf area was measured with a LI-COR model LI-3000 (LI-3100 in 1982) area meter from a subsample of the plants harvested each sample date. Three plants were harvested on each sample date in 1979, four in 1980 and five in 1981 and 1982. Green leaf area index was computed for each plot as the ratio o green leaf area to soil area. After physiological maturity, as indicated by black layer formation, grain was harvested. Harvested areas included the middle rows of each plot. Grain yield was computed on an area basis (Mg/ha) and adjusted to 15.5% moisture.

Table 1. Summary of the experimental conditions for the four years that comprised the study of spectrally predicted estimators of APAR′.

Experiment Number	Year	Planting Dates	Planting Densities	Hybrid	Soil Types
			10^3 plants/ha		
I	1979	2, 16, 30 May	25, 50, 75	Beck 65X	Typic Argiaquol Udollic Ochraqualf
II	1980	7, 22 May 11 June †	25, 50, 75	Beck 65X	Typic Argiaquol Aeric Ochraqualf
III	1981	8, 29 May 11, 29 June	25, 50, 75	Beck 65X	Typic Argiaquol
IV	1982	14 May 8, 24 June	25, 50, 75, 100	Adlers 30X	Typic Argiaquol
V	1982	14 May 24 June	50, 100	Adlers 30X	Typic Argiaquol

† Additional plantings of the 50,000 plants/ha density were planted on 16 and 29 May, 18 June and 3 July 1980.

Measurements of Absorbed PAR

Photosynthetic photon flux densities (PPFD) were measured under clear sky conditions (cloud cover less than 10% with no clouds within 10^o 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 on the handle of the sensor allowed the observer to trigger automatic data acquisition by a data logger (Omnidata Polycorder Model 516). The time of each measurement (hour, min, s) was also automatically recorded. 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. Transmitted PAR (TPAR), reflected PAR from the canopy and soil surface ($RPAR_{cs}$), and reflected PAR from the soil surface under the canopy ($RPAR_s$) were computed as proportions of the incident PAR (PAR_o):

$$TPAR' = (TPAR/PAR_o) \quad , \tag{5}$$

$$RPAR'cs = (RPAR_{cs}/PAR_o) \quad , \tag{6}$$

$$RPAR's = (RPAR_s/PAR_o) \quad , \tag{7}$$

and will be cited as such throughout the following discussion unless otherwise noted.

PAR_o and TPAR' were measured in Experiment V at weekly (when possible) intervals throughout the growing season under clear sky conditions within 0.5 hr of solar noon. TPAR' was measured at three sites per plot. At each site the sensor was positioned perpendicular to the row direction and centered on the row. Each set of TPAR' measurements consisted of four individual measurements as the sensor was incremented at nearly equal intervals between plants within a row. TPAR' was computed as the mean of four individual measurements and PAR_o (Eq. 5). PAR_o was measured either above or outside of the canopy within 20 s of the measured TPAR. TPAR' measured with the 100 cm sensor length varied from that of the ideal sensor length (Warren Wilson, 1981) of 76 cm by less than 7% when less than 8 leaves were emerged (stage V8). After this stage leaves overlapped between rows and few significant differences were detected.

$RPAR_s$ and $RPAR_{cs}$ varied less than 6% during the growing season. $RPAR_{cs}$ 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. $RPAR'_s$ is the portion of the PAR_o transmitted through the canopy that is reflected 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 (Hipps et al., 1983) resulted in a shadow cast on the soil surface by the sensor. $RPAR'_s$ was estimated as:

$$RPAR'_s = (RF_s)(TPAR') \qquad (8)$$

where, RF_s is the reflectance factor of bare soil. RF_s was measured with the sensor inverted and leveled 35 cm above the soil surface at a site adjacent to the plots. RF_s of the dry soil (Typic Argiaquoll) was measured as 9.3 ± 0.5% (n=270). $RPAR'_s$ (Eq. 8) ranged from 0.1 of PAR_o when no canopy cover was present to less than 0.01 of PAR_o under a full canopy cover. Absorbed PAR (Eq. 9) was computed:

$$APAR' = 1.0 + RPAR'_s - TPAR' - RPAR'_{cs} \quad . \qquad (9)$$

Spectral Measurements

Radiance measurements, used to determine reflectance factors (RF), were acquired with a four band radiometer (Exotech model 100), that simulates the Landsat MSS bands (MSS4, 500 to 600 nm; MSS5, 600 to 700 nm; MSS6, 700 to 800 nm; MSS7, 800 to 1100 nm). Measurements were made throughout each growing season at approximately weekly intervals. Biehl and Robinson (1983) describe the conditions and procedures for obtaining the RF data. The radiometer has a 15° field of view.

The radiometers were attached to a boom mounted on a pickup truck and elevated 7.6 m (5.2 m in Experiment I) above the soil surface. Data were taken only when there were no clouds in the vicinity of the sun and when the solar elevation was at least 45°. Measurements were made after the instruments were leveled for a nadir view angle. Each set of measurements consisted of two measurements, one centered over a row and one centered between rows of the canopy to better estimate the overall canopy response (Daughtry et al., 1982). Three sets of measurements were made for each of the plots included in Experiment V.

Analysis of Data

APAR' measured in Experiment V was regressed as a function of green LAI and each of the three spectral transformations. The relationships developed were tested on the data collected in Experiments I through IV (Table 1) The daily amount of APAR (moles m^{-2}) was estimated as:

$$APAR = APAR' \; PPFD \qquad (10)$$

where APAR' is the predicted portion of the daily incident PAR (PPFD) that was absorbed by the canopy.

The green LAI and vegetation indices, their respective predicted values of APAR' and estimated values of APAR (moles m^{-2}) were linearly interpolated and cumulated from planting to maturity for each field plot included in the test data. One plot in Experiment I and eight in

Experiment II lodged severely and were excluded. Representative values of reflectance from bare soil and senesced vegetation were used respectively to begin and end seasonal interpolations of APAR'. Final grain yield and the results of the seasonal cumulation of agronomic and vegetation indices and their estimates of APAR' were averaged over the replicates. The variance in final grain yield associated with the cumulated agronomic and vegetation indices was examined.

RESULTS AND DISCUSSION

Relation of APAR′ to LAI and Spectral Variables

Two distinct relationships between APAR′ and LAI were detected (Fig. 1). APAR′ increased as a function of green LAI from planting to a maximum at anthesis or silking (stage R1) then decreased at a different rate to maturity. Beer's Law described the relationship between APAR′ and LAI from planting to silking (Asrar et al., 1984; Hipps et al., 1983; and Norman, 1980). Similar relationships between APAR′ and LAI were reported by Hatfield et al. (1984) for wheat canopies. Maximum APAR′ for wheat canopies also occurred near anthesis. The different relationships before and after silking are due to the absorption of PAR by nongreen vegetation after silking as senescence occurs. Relationships developed after silking between APAR′ and LAI (or the vegetation indices) overestimate the APAR′ of green vegetation and hence the utilization of incident PAR by the canopy. Even at maturity, when no green leaves were present, greater than 60% of the incident PAR was absorbed by nongreen leaves, stems, and other plant parts (Fig. 1).

Quadratic equations (Table 2) adequately described the relationship between APAR′ and the spectral variables RATIO (Fig. 2), ND (Fig. 3), and GI (Fig. 4). Only data obtained between the planting and silking stages of crop development were included in the development of these equations. The equations developed in Experiment V were tested with the data of Experiments I through IV. APAR′ predicted from measured LAI was highly correlated with APAR′ predicted with the three vegetation indices (Table 3).

A canopy with north-south row orientation has a minimum APAR′ at solar noon (Hipps et al., 1983). Thus daily estimates of the quantity of absorbed PAR (moles/m2) based on the proportion of absorbed PAR (APAR′) measured at solar noon probably under-predict the energy available to the crop before a full canopy has developed. When LAI of wheat is high (i.e., > 4.0), the absorption of PAR remains high throughout the day and is largely independent of solar angle. In wheat canopies with low LAI, proportionately more PAR was absorbed on cloudy days than on clear days (Hipps et al.,1983). Nevertheless Hipps et al.(1983) reported that a single equation adequately described absorbed PAR as a function of LAI.

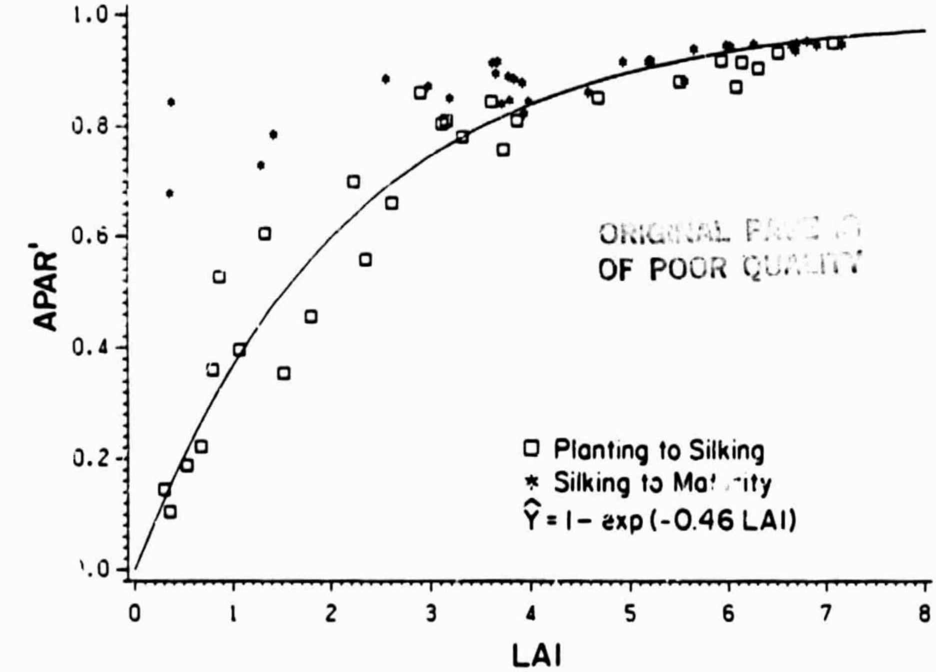

Figure 1. Relation between absorbed PAR and leaf area index for growth (planting to silking) and senescent (silking to maturity) periods of corn (Experiment V). The solid line indicates the predicted values of APAR′ for the interval from planting to silking.

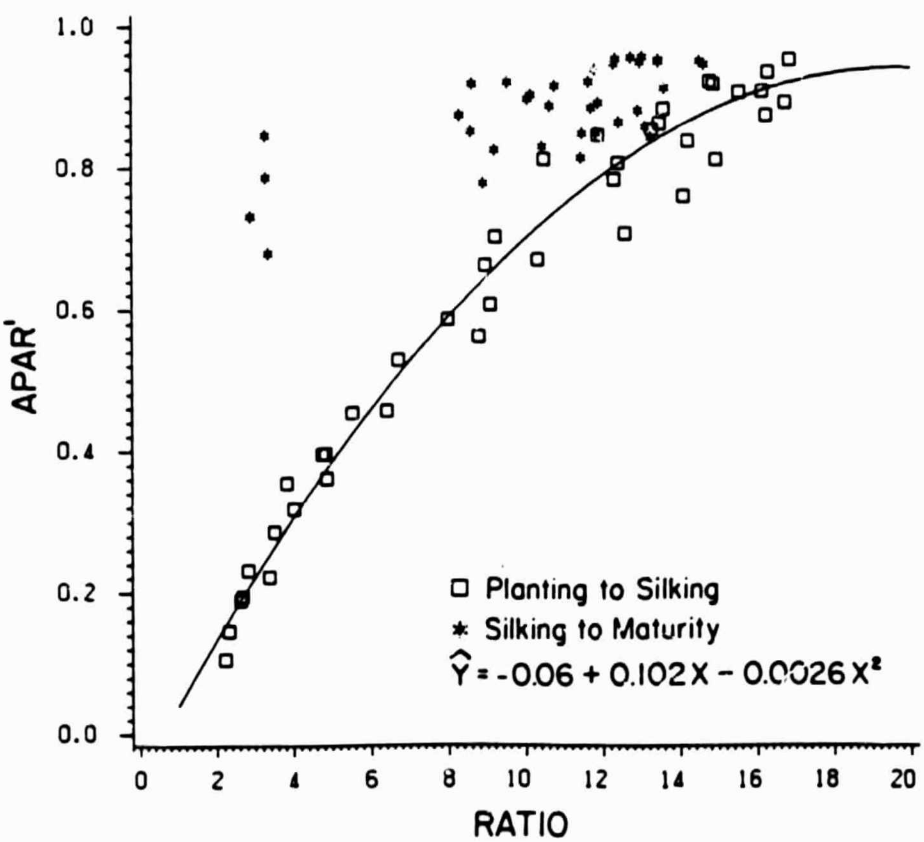

Figure 2. Relation between absorbed PAR and RATIO for growth (planting to silking) and senescent (silking to maturity) periods of corn development (Experiment V). The solid line indicates the predicted values of APAR′ for the interval from planting to silking.

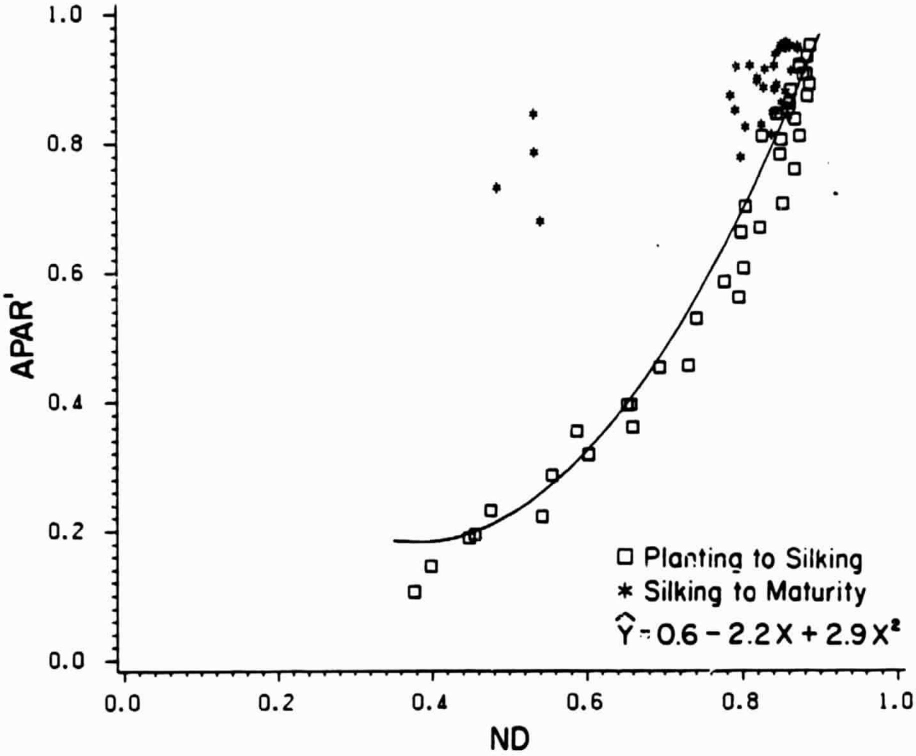

Figure 3. Relation between absorbed PAR and normalized difference (ND) for growth (planting to silking) and senescent (silking to maturity) periods of corn development (Experiment V). The solid line indicates the predicted values of APAR′ for the interval from planting to silking.

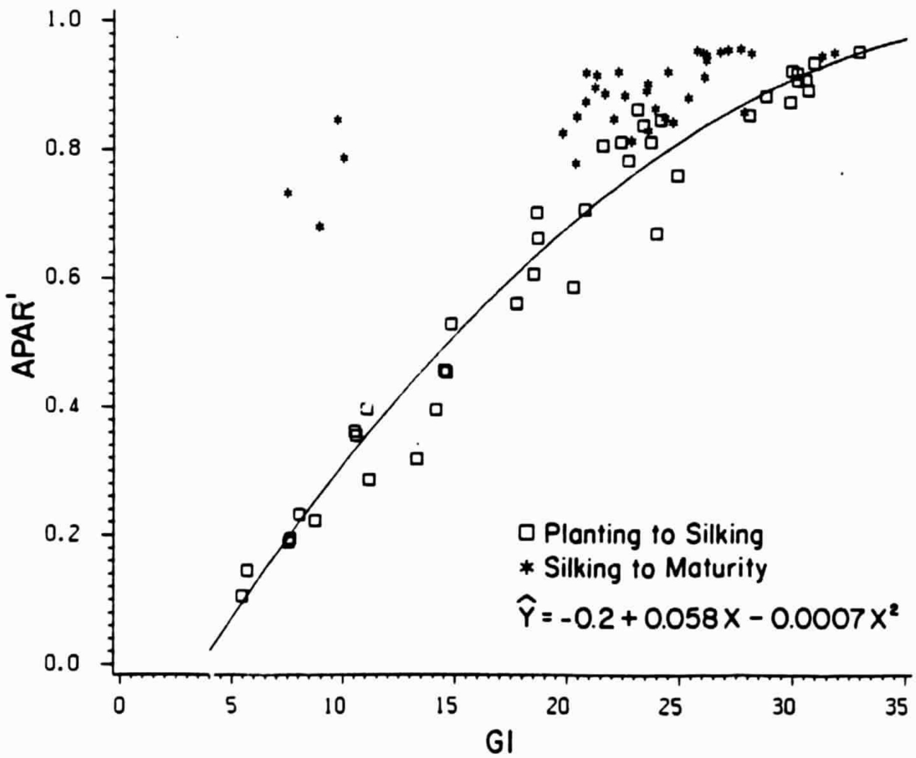

Figure 4. Relation between absorbed PAR and greenness index (GI) for growth (planting to silking) and senescent (silking to maturity) periods of corn development (Experiment V). The solid line indicates the predicted values of APAR′ for the interval from planting to silking.

Table 2. Quadratic regression equations that were developed from data of Experiment V to predict APAR′, from planting to silking, with spectrally predicted vegetation indices (n=40).

estimator	coefficients			RMSE	F	R^2
	b	b	b	(%)		
GI	-0.20†	0.058	-0.0007	5.3	485.2	0.96
ND	0.6	-2.2	2.9	4.7	613.7	0.97
RATIO	-0.06	0.102	-0.0026	4.4	709.5	0.97

† All coefficients were significant at the 0.01 level of probability, except b of the RATIO quation, which was significant at 0.1.

Table 3. Correlation coefficients that resulted from the prediction of APAR′ for the test years (Experiments I through IV) with the equations developed from the data of Experiment V (n=561).

	predictors of APAR′			
	LAI	GI	ND	RATIO
LAI	1.00†			
GI	0.96	1.00		
ND	0.92	0.91	1.00	
RATIO	0.94	0.94	0.99	1.00

† All correlations were significant at the 0.01 level of probability.

Relation of Yield to Cumulative LAI and APAR

The seasonal duration of leaf area is a better indicator of grain yields than maximum LAI produced (Daughtry et al., 1983). Seasonal cumulations of daily LAI or any of the three vegetation indices were associated with greater than 50% of the variation in corn grain yields (Table 4). LAI of a crop represents only the amount of photosynthetic tissue present in the canopy and does not account for productivity. The use of only daily incident PAR (Fig. 5a) or APAR' (Fig. 5b) in a model of crop productivity clearly misrepresents the actual amount of PAR absorbed (Fig. 5c). Cumulated daily APAR was associated with over 66% of the variation in final grain yields measured from four years of test data (Table 4). The cumulated daily APAR (ΣAPAR), computed with APAR' predicted from the normalized difference (Eq. 2) and daily incident PAR, was associated with 73% of the variation in observed grain yields (Fig. 6). A portion of the unexplained variation in grain yields is due to the effects of meteorological variables not included in this model on plant growth and development. The various planting date and plant density treatments would also be associated with a portion of the unexplained variation in the grain yields.

In summary, the intent of this study was to develop and examine the performance of several spectral estimators of one specific variable often included in models of crop yield (APAR'). The relationships between final grain yield and APAR indicate that all three of the vegetation indices that estimate APAR' from canopy spectral reflectance provided similar information about the portion of incident PAR that was absorbed by crop canopies. Spectral estimators of APAR, interpolated on a daily basis and cumulated from planting to maturity, were associated with as much of the variation in final grain yield as APAR estimated with measured LAI. These results suggest that APAR may be estimated from canopy spectral reflectance for large areas where direct measurements of LAI would be prohibitive. Thus models of crop yields which require estimates of absorbed PAR may be implemented and evaluated.

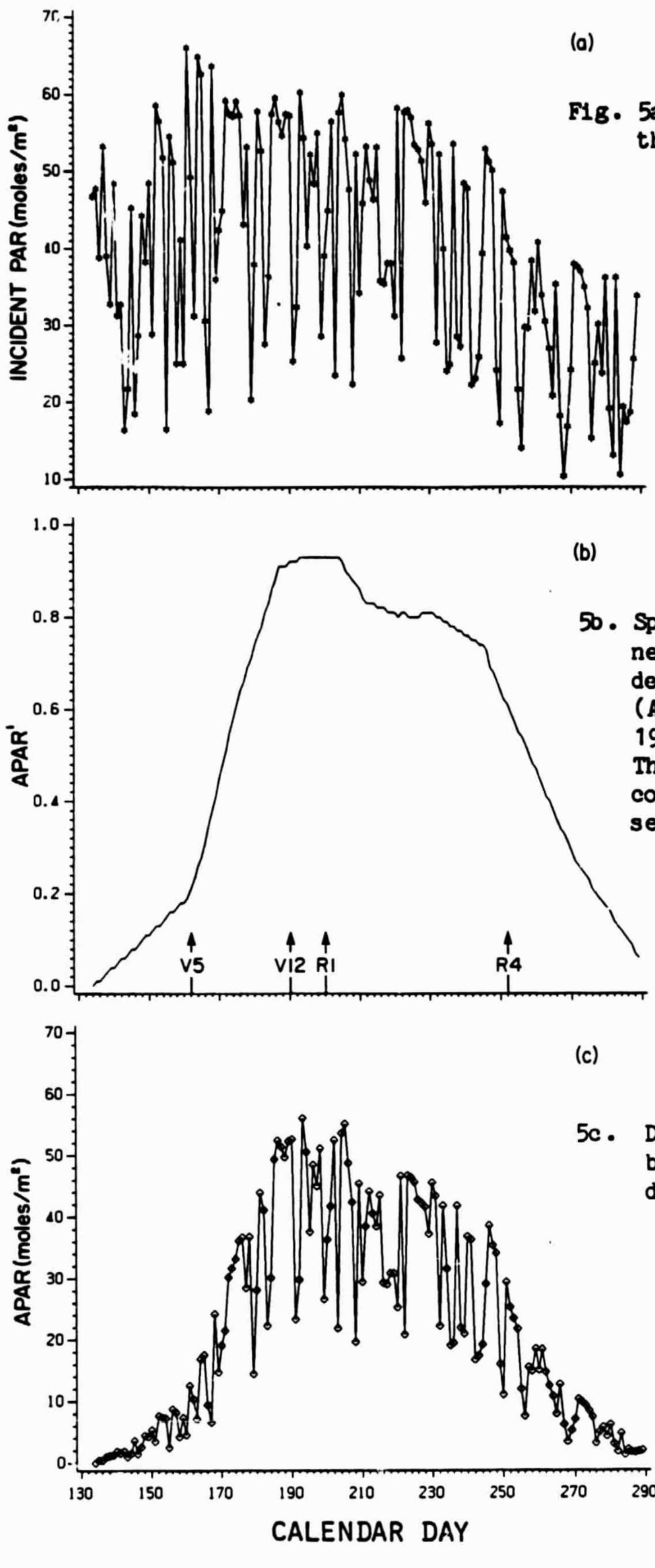

Fig. 5a. Daily incident PAR for the 1982 growing season.

5b. Spectrally predicted (greenness index) portion of incident PAR absorbed by corn (APAR') planted on 14 May 1982 at 100,000 plants/ha. The development stage of the corn is indicated for selected observation dates.

5c. Daily amount of PAR absorbed by a corn canopy (product of daily incident PAR and APAR').

Table 4. Results of linear regression of corn grain yields of Experiments I through IV on seasonally cumulated values of agronomic and vegetation indices and their respective estimates of canopy absorption of PAR (n=79).

variable	RMSE	F	r^2
	Mg/ha		
LAI	2.3	98.4	0.56
GI	2.3	100.4	0.56
ND	2.2	105.6	0.58
RATIO	2.3	101.1	0.57
$\Sigma APAR_{LAI}$	1.8	193.3	0.72
$\Sigma APAR_{GI}$	2.0	151.3	0.66
$\Sigma APAR_{ND}$	1.8	209.2	0.73
$\Sigma APAR_{RATIO}$	2.0	146.4	0.66

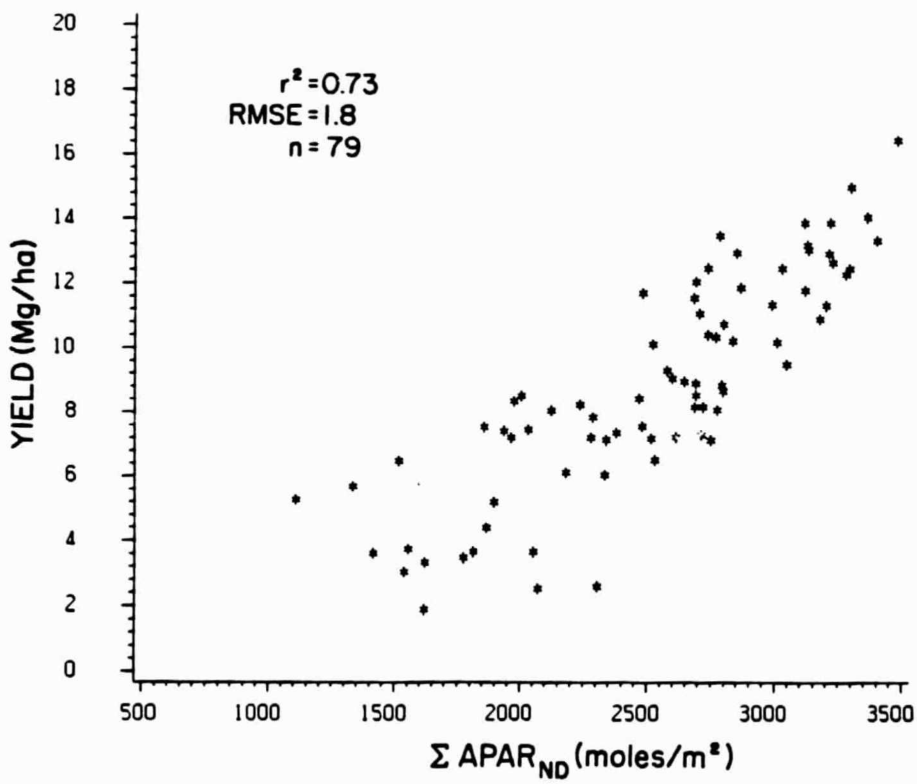

Figure 6. Grain yields of corn from Experiments I through IV as a function of absorbed photosynthetic photon flux density ($\Sigma APAR$).

REFERENCES

Arkin, G.F., Vanderlip, R.L., and Ritchie, J.T. (1975), A dynamic sorghum growth model, Trans. Am. Soc. Agric. Eng. 19:622-626,630.

Asrar, G., Fuchs, M., Kanemasu, E.T., and Hatfield, J. L. (1984), Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat, Agron. J. 76:300-306.

Biehl, L.L., and Robinson, B.F. (1983), Data acquisition and preprocessing techniques for remote sensing field research, Proc. Soc. Photo-Optical Instr. Engr. 356:143-149. LARS Technical Report 082182.

Coelho, D.T., and Dale, R.F. (1980), An energy-crop growth variable and temperature function for predicting corn growth and development: planting to silking, Agron. J. 72:503-510.

Daughtry, C.S.T., Gallo, K.P., and Bauer, M.E. (1983), Spectral estimates of solar radiation intercepted by corn canopies, Agron. J. 75:527-531. LARS Technical Report 030182.

Daughtry, C.S.T., and Hollinger, S.E. (1984), Costs of measuring leaf area index of corn, Agron. J. (in press). LARS Technical Report 030784.

Daughtry, C.S.T., Vanderbilt, V.C., and Pollara, V.J. (1982), Variability of reflectance measurements with sensor altitude and canopy type, Agron. J. 74:744-751. LARS Technical Report 111481.

Hatfield, J.L., Asrar G., Kanemasu, E.T. (1984), Intercepted photosynthetically active radiation estimated by spectral reflectance, Remote Sensing of Environ. 14:65-75.

Hipps, L.E., Asrar, G., and Kanemasu, E.T. (1983), Assessing the interception of photosynthetically active radiation in winter wheat, Agric. Meteor. 28:253-259.

Kollenkark, J.C., Vanderbilt, V.C., Daughtry, C.S.T., and Bauer, M.E. (1982), Influence of solar illumination angle on soybean canopy reflectance, Appl. Optics. 21:1179-1184. LARS Technical Report 021681.

MacDonald, R.B., and Hall, F.G. (1980), Global crop forecasting, Science 208:670-679.

McCree, K.J. (1966), A solarimeter for measuring photosynthetically active radiation, Agr. Meteorol. 3:353-366.

McCree, K.J. (1972), Test of current definitions of photosynthetically active radiation against leaf photosynthesis data, Agric. Meteorol. 10:443-453.

Norman, J.M. (1980), Interfacing leaf and canopy light interception models, in J.D. Hesketh and Jones, J.W. (eds.), Predicting photosynthesis for ecosystem models, Vol. 2, p. 49, CRC Press, Boca Raton, FL, U.S.A.

Perry, C.R., Jr., and Lautenschlager, L.R. (1984), Functional equivalence of spectral vegetation indices, Remote Sensing of Environ. 14:169-182.

Pinter, P.J., Jr., Jackson, R.D., Idso, S.B., and Reginato, R.J. (1981), Multidate spectral reflectance as predictors of yield in water stressed wheat and barley, Int. J. Remote Sensing 2:43-48.

Rice, D.P., Crist, E.P., and Malila, W.A. (1980), Applicability of selected wheat remote sensing technology to corn and soybeans, Final Report No. 124000-9-F, Environmental Res. Inst. of Michigan, Ann Arbor, MI 48107, U.S.A.

Ritchie, S.W., and Hanway, J.J. (1982), How a corn plant develops, Iowa State Univ. Special Report No. 48, Coop. Ext. Service, Ames, IA, U.S.A.

Stapper, M., and Arkin, G.F. (1979), CORNF: A dynamic growth and development model for maize (Zea mays L.), Program model documentation No. 80-2, Texas Agric. Exp. Stn., Blackland Resr. Center, Temple, TX.

Steven, M.D., Biscoe, P.V., and Jaggard, K.W. (1983), Estimation of sugar beet productivity from reflection in the red and infrared spectral bands, Int. J. Remote Sensing 4:325-334.

Szeicz, G. (1974), Solar radiation for plant growth, J. Appl. Ecol. 11:617-637.

Tucker, C.J., Holben, B.N., Elgin, J.H., Jr., and McMurtrey, J.E., III (1980), Relationship of spectral data to grain yield variation, Photogram. Engr. and Remote Sensing 46:657-666.

Walburg, G., Bauer, M.E., Daughtry, C.S.T., and Housley, T.L. (1982), Effects of nitrogen nutrition on the growth, yield, and reflectance characteristics of corn canopies, Agron. J. 74:677-683. LARS Technical Report 030381.

Warren Wilson, J. (1981), Analysis of light interception by single plants, Ann. Botany 48:501-505.