GODDARD GRANT
IN-43-CR
106159
22 P.

LARS Report 071587
NASA - Goddard Space Flight Center
Grant Number NAG 5-771

Final Report

Estimating Scattered and Absorbed Radiation in Plant Canopies by Remote Sensing

by

C. S. T. Daughtry and K. J. Ranson

(NASA-CR-181390) ESTIMATING SCATTERED AND ABSORBED RADIATION IN PLANT CANOPIES BY REMOTE SENSING Final Report (Purdue Univ.) 22 p Avail: NTIS HC A03/MF A01 CSCL 02F

N88-11205

Unclas

G3/43 0106159

Laboratory for Applications of Remote Sensing
Purdue University
West Lafayette, Indiana 47907 USA

TABLE OF CONTENTS

I. INTRODUCTION 1

II. SIGNIFICANT ACCOMPLISHMENTS 3

A. Assessing Vegetation Characteristics with Multispectral Data 3

B. Indirect Estimation of Leaf Area Index of Soybeans 10

C. Estimating Big Bluestem Albedo from Directional Reflectance Measurement 15

III. PUBLICATIONS 20

I. INTRODUCTION

This document is the final report of the research results and accomplishments for Grant NAG-5-771, "Estimating Scattered and Absorbed Radiation in Plant Canopies by Remote Sensing" at the Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, IN from April 1986 to April 1987. Much of this research has been or soon will be published in scientific journals.

This report is divided into three sections including this introduction. In Section II we present three synopses which describe our significant research accomplishments during this grant. The first synopsis reviews the relationships of canopy characteristics to multispectral reflectance factors of vegetation and discusses several alternative approaches for incorporating spectrally-derived information into plant models. In the second synopsis we describe and evaluate a method to estimate leaf area index from measurements of radiation transmitted through plant canopies. In the third synopsis we estimate albedo of a big bluestem grass canopy from 75 directional reflectance factor measurements and evaluate effects of estimating albedo with substantially smaller subsets of these data. These data for big bluestem that we acquired in 1986 are available to other researchers upon request.

The section III we list the publications (both actual and anticipated) that were at least partially supported by this grant. For a more complete discussion of each of accomplishments described in section II, please refer to these publications.

II. SUMMARY OF ACCOMPLISHMENTS

A. ASSESSING VEGETATION CHARACTERISTICS WITH MULTISPECTRAL DATA

C. S. T. Daughtry and K. J. Ranson

Introduction

Remotely sensed information can be used alone to infer the health or vigor of vegetation, however the acquisition of this information is frequently constrained by cloud cover and/or the spatial and temporal resolution of the sensor system. Most viable research approaches now focus on methods of incorporating multispectral data into models that can provide information about crop condition and yield. The synoptic, multidate views of agricultural land by multispectral satellite sensors provide the opportunity to acquire the data necessary to implement photosynthesis, evapotranspiration, and yield models over large geographic areas.

Several scenarios of how multispectral, meteorological, and ancillary data could be incorporated into physiologically-based models to depict limitations imposed on crop yields by weather and climate have been proposed (Wiegand, et al., 1986; Daughtry et al., 1983; Steven et al., 1983; Maas et al., 1985). Most remote sensing research has emphasized large area applications, however there is considerable potential to develop remote sensing capabilities to provide timely information on crop condition to farmers (Jackson, 1984).

In this paper we review the relationships of canopy characteristics to the reflectance factors of vegetation and discuss several alternative approaches for incorporating spectrally-derived information into plant process models for assessing the condition of vegetation.

Approach

Experiments, conducted over 5 years at Purdue University's Agronomy Farm (40^{o} 28' N, 87^{o} 00' W), are described fully elsewhere (Brooks and Daughtry, 1986; Daughtry et al., 1983; Gallo et al., 1985). Briefly adapted corn (*Zea mays L.*) and soybean (*Glycine max Merr.*) cultivars were planted in north-south rows on several dates and at several densities bracketing typical production practices for the eastern U.S. cornbelt. Agronomic variables, which were measured weekly, included leaf area index, stage of development, fresh and dry phytomass, plant height, and percent soil cover. Leaf area index was computed as the ratio of leaf area per unit soil area. After physiological maturity, grain was harvested, adjusted for 15.5% moisture, and reported as megagrams/hectare (Mg/ha).

Photosynthetic photon flux density (PPFD) was measured under clear skies with a line quantum sensor (LI-COR 191SB). The sensor is cosine corrected and responds to radiation in the 400 to 700 nm wavelength region. PAR incident (I_O), transmitted through the canopy to the soil surface (T_S), reflected from the canopy (R_C) and reflected from the soil (R_S) were measured under clear sky conditions within 0.5 h of solar noon on selected dates throughout the growing season using procedures described by Gallo and Daughtry (1986). The fraction of incident PAR (F) that was absorbed by the crop was calculated using the following equation:

$$F = [(I_O + R_S) - (T_S + R_C)]/I_O.$$

Radiance measurements, used to determine reflectance factors (RF), were acquired with Landsat Multispectral Scanner (Exotech 100) and Landsat Thematic Mapper (Barnes 12-1000) radiometers throughout the growing season at approximately weekly intervals. Biehl and Robinson (1983) described the conditions and procedures for obtaining the reflectance factor (RF) data. The radiometers were attached to a boom mounted on a pick-up truck and elevated 7.6 m above the soil surface. Data were taken only when there were no clouds over or in the vicinity of the sun and when the solar elevation was at least 45^{o}.

Results and Discussion

Solar Radiation Interception

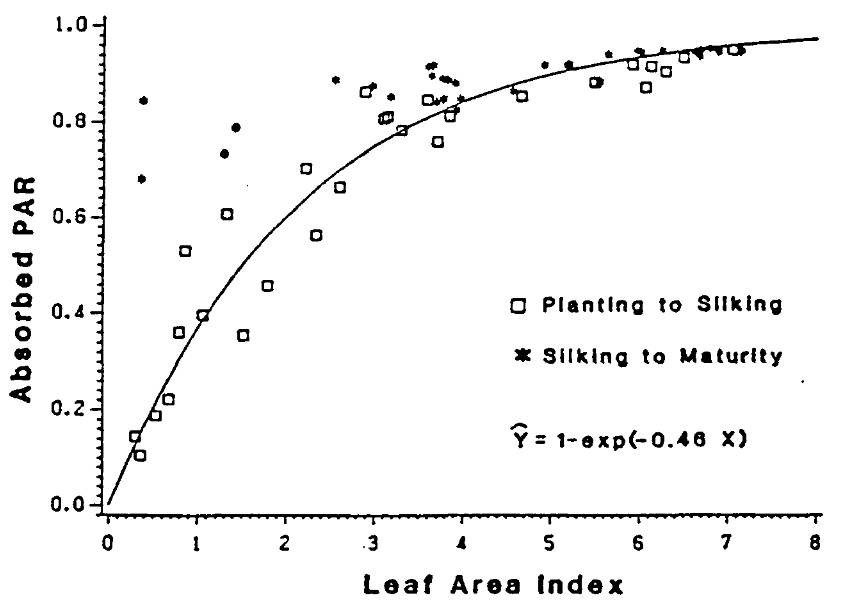
Solar radiation is the source of energy for photosynthesis and evapotranspiration. Solar radiation is available as an energy source for plants only when it interacts with green leaves or other chlorophyll containing plant structures. Not all of the energy in the solar radiation is capable of supporting photosynthesis in plants. Only radiation in the 400-700 nm wavelength interval is photosynthetically active radiation (PAR). The proportion of PAR in solar radiation is typically 0.5 (McCree, 1972).

Absorption of radiation by crop canopies is dependent on the stage of development and leaf area index of the crop. Initially as LAI increases, absorption of PAR increases rapidly (Fig. 1). As LAI continues to increase absorption of radiation asymptotically approaches

100%, where all of the incident PAR is absorbed by vegetation before the radiation reaches the soil. The relationship between LAI and interception of radiation has been described in terms of Beer's Law for wheat (Asrar et al., 1984), for corn (Gallo et al., 1985) and for soybeans (Brooks and Daughtry, 1986).

As green LAI decreased during senescence, absorption of radiation decreases slowly (Fig. 1). Even at physiological maturity of corn, when no green leaves were present, more than 60% of PAR was absorbed by nongreen leaves, stems and other plant parts (Gallo et al., 1985). Thus the relationships of absorbed PAR to greenness (Fig. 2) and ND (e.g., Asrar et al 1984) typically are biphasic. Two equations are required to describe absorbed PAR as a function of increasing and decreasing greenness (or ND), respectively. The hysteresis in Figures 1 and 2 is due to the spectral reflectance and PAR absorption of senescent vegetation.

Figure 1. Relation between absorbed PAR and leaf area index for corn.



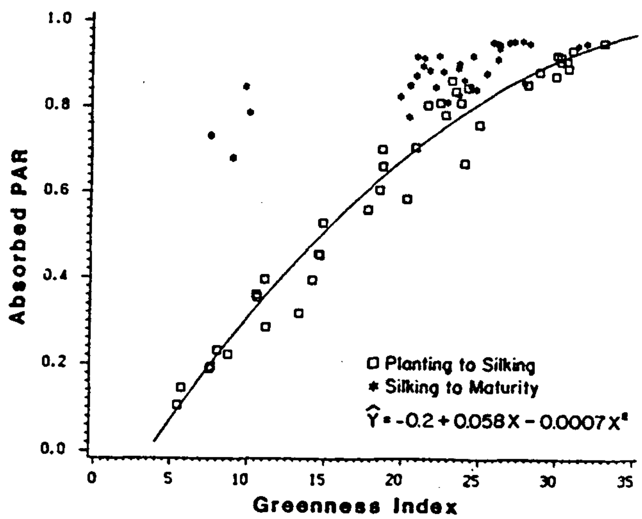


Figure 2. Relation between absorbed PAR and spectral vegetation index, greenness, for corn.

The amount of PAR intercepted by plants was significantly greater for soybeans planted in narrow rows than in wide row spacings. Early planted soybeans also intercepted more PAR during their life cycle than late planted soybeans. The amount of intercepted PAR cumulated from planting to physiological maturity was highly correlated with total dry phytomass and grain yield ($r^2 = 0.86$). Mean efficiency of conversion of intercepted radiation into total above ground dry phytomass was greatest for soybeans in the narrowest row spacings (0.18 m). Mean efficiency during the reproductive stage was nearly double that during the vegetative stage (Table 2). This change in efficiency corresponded to increased demand for assimilates by the developing seeds and decreased root growth and nitrogen fixation in nodules on the roots.

Table 1. Mean efficiency of converting intercepted PAR into dry phytomass during the vegetative and reproductive stages of development of soybeans. Efficiency is expressed as the grams of above ground dry matter produced per mega Joule of intercepted PAR.

Row Spacing	VE-R1	VE-R5	VE-MDW*	R1-R5	R1-MDW
cm			g/MJ		
18	1.34	2.70	2.53	3.10	2.70
38	1.16	2.06	1.95	2.40	2.08
76	1.22	2.21	1.99	2.51	2.09

*Maximum dry weight.

Yield

The seasonal duration of leaf area is a more important indicator of grain yields than maximum LAI produced (Daughtry et al., 1983). Correlations of grain yields with spectral or agronomic data acquired on a single date during the season may be spurious and must be used with caution. Leaf area duration accounted approximately 50% of the variation in grain yields of corn. LAI of a crop represents only the amount of photosynthetic tissue present in the canopy but does not account for productivity. Canopies with low seasonal values of LAI absorbed the least PAR and produced the lowest grain yields.

When the daily photon flux density of PAR absorbed by the crop was estimated using multispectral data and accumulated over the season, absorbed PAR was associated with 81% of the variation on corn yields. In an independent test of this relationship, daily absorbed PAR was estimated using either LAI or one of several spectral vegetation indices and cumulated over the growing season. In the test case greater than 65% of the variation in corn yields were associated with absorbed PAR estimated by the spectral indices (Table 2). The quantity of energy absorbed by a crop was more indicative of yields than LAI. High correlations of yields and various cumulated spectral variables also have been reported for wheat (Pinter et al., 1981), sugar beets (Steven et al., 1983), and corn (Daughtry et al., 1983; Gallo et al., 1985).

Table 2. Results of linear regression of corn grain yields of test years on seasonally cumulated values of agronomic and vegetation indices and their respective estimates of canopy absorption of PAR (n = 79).

Variable	RMSE (Mg ha^{-1})	F	r^2
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
$APAR_{LAI}$	1.8	193.3	0.72
$APAR_{GI}$	2.0	151.3	0.66
$APAR_{ND}$	1.8	209.2	0.73
$APAR_{RATIO}$	2.0	146.4	0.66

Plant response to solar radiation is confounded with the effects of temperature and moisture on plant growth and yields. Thus the applicability of models based solely on spectral data are limited. Several approaches have been proposed to use multispectral data in conjunction with meteorological, soils, and ancillary data in models to predict crop yields.

For example, spectral estimates of intercepted radiation may be incorporated into the Energy-Crop Growth (ECG) model (Coelho and Dale, 1980). This model combines the concept of intercepted solar radiation with a moisture stress term and a temperature function to predict growth and development of corn. Models using the sum of the daily values of ECG were associated with more of the variation in corn yields than models which used only spectral or only meteorological data. A portion of the unexplained variation in grain yields is due to the effects of meteorological variables not included in the ECG model on plant growth and development. The wide range of planting dates and plant density treatments is also associated with a portion of the unexplained variation in grain yields.

When moisture and/or temperature limit crop production, approaches, like the ECG model, should be superior to approaches using only spectral or only meteorological data for predicting crop yields. Maas et al. (1985) described a strategy for making large area yield estimates using a simplified crop growth model with weather and remotely sensed data as inputs. The remotely sensed data was used (1) to update the state variables of the model based on multispectral vegetation indices and (2) to compute crop stress based on canopy temperature measurements. Periodic updating of the state variables in the model with remotely sensed data improved the model's estimates of LAI, phytomass and grain yields and allowed predicted crop growth to closely approximate observed crop growth.

Summary

The concept of combining spectral estimates of canopy characteristics with meteorological and ancillary data should permit implementation of physiologically-based crop models for large areas.

A production forecasting system using meteorological and spectral data could exploit the frequent temporal sampling typical of weather data with the high spatial resolution typical of earth observing satellites (Daughtry et al., 1983; Maas et al., 1985; Wiegand et al., 1986). Multispectral data from satellites could form the basis for estimating crop production over regions where ground observations are difficult or too costly to obtain directly.

References

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

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

Brooks, C.C. and C.S.T. Daughtry 1986. Light interactions with soybean canopies. In C.S.T. Daughtry and K.J. Ranson (eds) Measuring and modeling biophysical and optical properties of diverse vegetative canopies. Tech Report 043086. Purdue University, West Lafayette, IN.

Coelho, D.T. and R.F. Dale. 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., K.P. Gallo, and M.E. Bauer. 1983. Spectral estimates of solar radiation intercepted by corn canopies. Agron. J. 75:527-531.

Gallo, K.P., and C.S.T. Daughtry. 1986. Techniques for measuring intercepted and absorbed photosynthetically active radiation in corn canopies. Agron. J. 78:752-756.

Gallo, K.P., C.S.T. Daughtry, and M.E. Bauer. 1985. Spectral estimates of absorbed photosynthetically active radiation in corn canopies. Remote Sens. Environ. 17:221-232.

Jackson, R.D. 1984. Remote sensing of vegetation characteristics for farm management. Proc. Soc. Photo-optical Instr. Engr. 475:81-96.

Maas, S.J., A.J. Richardson, C.L. Wiegand, and P.R. Nixon. 1985. Use of plant, spectral, and weather data in modeling corn growth. Proc. 19th Intl Symp. Remote Sensing of Environment, Ann Arbor, MI 21-25 October 1985.

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

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

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

Wiegand, C.L., A.J. Richardson, and P.R. Nixon. 1986. Spectral components analysis: A bridge between spectral observations and agrometeorological crop models.

II. B. INDIRECT ESTIMATION OF LEAF AREA INDEX OF SOYBEANS

C. C. Brooks and C. S. T. Daughtry

Introduction

The interception and distribution of solar radiation within a crop canopy is one of the most important environmental factors influencing crop growth and development (Fitter and Hay, 1981). The vast majority of energy utilized in photosynthesis is captured by plant leaves. Only solar radiation in the 400 to 700 nm wavelength region contribute to photosynthesis and is generally referred to as photosynthetically active radiation (PAR).

Weber et al. (1966) attributed seed yield increases in narrower row widths to greater interception of PAR earlier in the growing season. Shibles and Weber (1966) suggested that LAI values in excess of that required to intercept 95% of the incoming PAR are not detrimental to dry matter production. Therefore, if factors other than light are not limiting, plant growth is proportional to the amount of intercepted radiation by a plant (Daughtry et al., 1983; Gallo et al., 1985).

Sakamoto and Shaw (1967), using research done by Monsi and Saeki (1953) and Davidson and Philip (1958), examined the relative light intensity throughout a soybean canopy as it related to the cumulative leaf area index . This relationship may be described as:

$$I/I_o = e^{-k(LAI)} \qquad (1)$$

where:

I = radiant energy received at the bottom of an increment of leaf area index (LAI),

I_o = incident radiant energy at the top of the canopy,

k = extinction coefficient.

Reported extinction coefficients range from 0.25 to 2.00 due to combining many crop and environmental parameters including: incident radiation (magnitude, wavelength, and sun angle), spectral properties of the soybean cultivar, canopy structure (LAI, foliage distribution, and size and shape of the leaflets), and foliage movement (wind, wilting, and phototropism).

Adams and Arkin (1977) suggested that measurements made to calculate k should be performed near solar noon when changes in sun angles result in the least change in k. However, Warren Wilson (1960) aptly reported that measurements of k at solar noon (maximum daily solar elevation angle and solar azimuth angle of 180^o) varied more than k values at low sun elevation angles. Variations in k for different strata within canopies are due to changes in leaflet inclination angles (Luxmoore et al., 1971). Different cultivars of the same species may have significantly different k values (Ogbuehi and Brandle, 1982; Sakamoto and Shaw, 1967).

The objectives of this study were to develop and evaluate a method of estimating LAI of soybeans *(Glycine max Merr.)* from measurements of transmitted PAR. The method proposed in this paper requires only a few minutes to determine both LAI and transmitted PAR.

Approach

In 1982 and 1983 experiments were conducted on the Purdue University Agronomy Farm (40^{o} 28′ N, 87^{o} 00′ W) near West Lafayette, Indiana. The experimental design was a randomized, complete block design which included two blocks, two planting dates, two row widths (38 and 76 cm) in 1982 , and three row widths (18, 38, and 76 cm) in 1983 . All rows were planted in a north-south direction.

Plant height, leaf area index (LAI), stage of development, total fresh and dry phytomass, dry weight of stems (including petioles), pods, and green leaf blades were measured weekly. Daily estimates of LAI (ELAI) were produced by smoothing the weekly values with a quasi-hermite spline function (IMSL, 1982).

Transmitted PAR was measured under clear sky conditions (cloud cover less than 10% with no clouds within 10^{o} of the sun) with a modified line quantum sensor (LI-COR 191SB). The modifications included a handle, a bubble level, and a data logger (Omnidata Polycorder 516) to record data and time automatically (Gallo and Daughtry, 1986). The proportions of incident PAR transmitted (TPAR) through the canopy to the soil were measured at several different locations within each plot .

The data from the two years were divided into calibration and test data sets. The number of observations and range of the data were approximately equal for both sets of data. Extinction coefficients were determined for each 10^{o} bin in solar zenith angle (θs) for the calibration data. LAI was predicted for the test data using Eq 2

$$LAI = [\ln(TPAR)]/-k \qquad (2)$$

where:

TPAR = proportion of incident PAR received at the soil surface
k = extinction coefficient.

Six methods were used to determine the "best fit" (highest r^2, lowest bias, and highest accuracy). The first model used all of the ELAI and TPAR data. The second method (Model 2) weighted ELAI by the pathlength of a solar ray passing through the canopy (i.e., ELAI divided by cosine of solar zenith angle).

The third and fourth models were similar to models 1 and 2, respectively, but used only data acquired when direct sun light was attenuated by the canopy (i.e., the shadow cast by plants in one row extended to the adjacent row). The soil surface is always shadowed when the projected solar angle (θ_{sp}) exceeds the critical angle (θ_c). Projected solar angle was defined by Kollenkark et al. (1982) as:

$$\theta sp = \tan^{-1} (\tan \theta_s \ \sin \phi_{sr}) \qquad (3)$$

where:

θ_s = solar zenith angle

ϕ_{sr} = |solar azimuth - row azimuth angle|.

The critical angle (Oc)is defined as:

$$\theta_c = \tan^{-1} \quad (RS - PW)/(PH - SH) \qquad (4)$$

where:

RS = row spacing,

PW = plant width,

PH = plant height,

SH = sensor height (assumed to be at the soil surface).

When θ_{sp} exceeds θ_c any direct radiation measured by the line quantum sensor must pass through gaps in the foliage.

The fifth and sixth models utilized the same procedures as the first and second models, respectively, but limited the data to a 10^o bin centered about 57.5^o solar zenith angle (i.e., 52.5 to 62.5^o). This solar zenith angle was chosen because extinction coefficients are least affected by leaf inclination angle at solar zenith angles of 57.5^o (Warren Wilson, 1960).

Results and Discussion

Table 1 shows the extinction coefficients developed on the calibration data when the regression was forced through zero. In Models 2, 4, and 6 when optical pathlength was considered, the extinction coefficients were less than that calculated in Models 1, 3, and 5 when no adjustments for pathlength were made. The extinction coefficients (k) in Table 1 are similar to those reported by other researchers on soybeans and other crops (Adams and Arkin, 1977; Luxmoore et al., 1971; Ogbuehi and Brandle, 1982; Sakamoto and Shaw, 1967).

The extinction coefficients determined from the calibration data were used to predict LAI for the test data. An analysis of errors for predicted minus actual LAI are presented in Table 2. The three models (Models 1, 3, and 5) with no correction for optical pathlength tended to under predict LAI (i.e., negative bias) while the other models with a pathlength correction over predicted LAI (positive bias). Except at very early growth stages, when the plant height is much less than the row width, the solar rays striking the sensor must be attenuated by the canopy. Under the conditions imposed by Models 5 and 6 the highest degree of linearity was achieved.

Although Model 5 had the lowest bias (e) and highest accuracy (lowest |e|) of all models tested, there were only 11 observations suitable for testing Models 5 and 6. With Model 5 LAI can be predicted from TPAR with an accuracy of ±0.5 LAI units. Nevertheless more observations at sun zenith angles of 57.5 ± 5° are needed before we can recommend this model.

Table 1. Regression parameters developed from Equation 5 on soybeans in calibration data set.

Model	Slope (k)	Adj r2	N
1 LAI	-0.718	0.81	98
2 LAI/cosθ_s	-0.569	0.86	98
3 LAI	-0.753	0.67	59
4 LAI/cosθ_s	-0.591	0.77	59
5 LAI	-1.027	0.96	11
6 LAI/cosθ_s	-0.599	0.95	11

Data for models 3 and 4 were collected when θ_{sp} -θ_c was positive. Data for models 5 and 6 were collected when θ_s was 57.5 ± 5°.

Table 2. Errors for predicting LAI of soybeans in test data using extinction coefficients in Table 1.

		$LAI_{predicted}$ - LAI_{actual}		
Model	N	e	|e|	S|e|
1 LAI	101	-0.462	1.001	0.031
2 LAI/cosθ_s	101	+0.794	1.087	0.012
3 LAI	73	-0.489	1.026	0.819
4 LAI/cosθ_s	73	+1.003	1.278	1.089
5 LAI	11	-0.435	0.499	0.489
6 LAI/cosθ_s	11	+0.740	0.804	0.828

Data for models 3 and 4 were collected when θ_{sp} -θ_c was positive. Data for models 5 and 6 were collected when θ_s was 57.5 ± 5°.

References

Adams, J.E., and G. F. Arkin. 1977. A light interception method for measuring row crop ground cover. Soil Sci. Soc. Am. 41:789-792.

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

Davison, J.L., and J.R. Phillip. 1958. Light and pasture growth. In Climatology and Microclimatology. Proc Canberra Symp. (1956). Arid Zone Research XI, UNESCO, Paris.

Gallo, K.P., and C.S.T. Daughtry. 1986. Techniques for measuring intercepted and absorbed photosynthetically active radiation in corn canopies. Agron. J. 78:752-756.

Gallo, K.P., C.S.T. Daughtry, and M.E. Bauer. 1985. Spectral estimates of absorbed photosynthetically active radiation in corn canopies. Remote Sens. Environ. 17:221-232.

IMSL Staff. 1982. Library Reference Manual. Edition 9. Vols 1-4. IMSL. Houston, TX.

Kollenkark, J.C., V.C. Vanderbilt, C.S.T. Daughtry, and M.E. Bauer. 1982. Influence of solar illumination angle on soybean canopy reflectance. Applied Optics 21:1179-1184.

Luxmoore, R.J., R.J. Millington, and D.B. Peters. 1970. Symap and net radiation in a soybean canopy. Agron. J. 62:830-831.

Monsi, M., and T. Saeki. 1953. Uber den lichtfaktor in den pflanzengasellschaften un seine Bedeutug fur die stoff produktion. Japan J. Bot 14:22-52.

Ogbuehi, S. N., and J. R. Brandle. 1982. Influence of windbreak shelter on soybean growth, canopy structure, and light relations. Crop Sci. 22:269-273.

Sakamoto, C.M. and R.H. Shaw. 1967. Light distribution in soybean canopies. Agron. J. 59:7-9.

Shibles, R.M. and C.R. Weber. 1966. Interception of solar radiation and dry matter production by various soybean planting patterns. Crop Sci. 6:55-59.

Warren Wilson, J. 1960. Inclined point quadrats New Phytology 59:1-8.

II. C. ESTIMATING BIG BLUESTEM ALBEDO FROM DIRECTIONAL REFLECTANCE MEASUREMENTS

J. R. Irons, K. J. Ranson and C. S. T. Daughtry

Introduction

Past efforts to estimate albedo from remote sensing data have been constrained by directional observations of reflected radiance in narrow spectral bands. Estimation of albedo from these observations generally required several simplifying assumptions. The assumptions included the use of narrow band data to represent reflectance across the short wave portion of the spectrum (0.3 to 3.0 um) and an assumption of isotropic (i.e., Lambertian) surface reflectance (Wiesnet and Matson, 1983). These assumptions may not be valid because reflectance from vegetation varies spectrally and is anisotropic. Several studies have shown that the assumption of isotropic reflectance can cause significant errors in estimates of albedo (Eaton and Dirmhirn, 1979; Kimes and Sellers, 1985; Irons et al., 1987).

Future sensors will be capable of providing data over the entire shortwave region from multiple view directions. The work reported here consists of an analysis of multiple direction reflectance data of big bluestem *(Andropogon gerardii)*, a tall perennial warm-season grass, to evaluate the variations of albedo with changes in solar zenith angle.

Approach

During the summer of 1986, reflected radiances of a uniform field of big bluestem were measured with a Barnes 12-1000 Modular Multiband Radiometer (MMR). Spectral reflectance factors were derived from ratios of the spectral radiance reflected from the grass to the spectral radiance reflected from a barium sulfate ($BaSO_4$) painted calibration panel according to the procedure outlined by Robinson and Biehl (1979).

The radiometer was mounted on a boom at 2.4 m above the soil and rotated through a series of 15 view zenith angles (out to 70^o on both sides of nadir in 10^o increments) in each of four azimuthal planes (i.e., 0-180, 45-225, 90-270, and 135-315 degrees) plus the principal plane of the sun for a total of 75 observations. Data were acquired several times per day on four dates during the growing season. The sequence of directional observations was repeated for a different location in the field. Data from both locations were acquired within 30 minutes. Mean spectral bidirectional reflectance factors from both locations were used to compute albedo.

Albedo is the ratio of total radiation flux reflected by a surface in all directions within the surrounding 2π steradian solid angle (i.e., hemisphere) to the total downwelling solar flux. Estimation of albedo of big bluestem from the spectral bidirectional reflectance data required two numerical integrations. First bidirectional reflectance factors for the shortwave (0.3 to 3.0 um) region were computed for 10 spectral bands. Bidirectional reflectance factors for seven spectral bands were estimated using reflectance factor data from the Barnes MMR. Reflectance factors in three remaining spectral bands (1.38 to 1.50 um, 1.85 to 2.08 um, and 2.35 to 3.00 um) were considered negligible based on *a priori* knowledge of typical vegetation reflectance spectra. Briefly, the first numerical integration computed a mean of reflectances in 10 spectral bands weighted by the downwelling solar flux in each of the bands. Solar flux for a clear rural atmosphere (23 km visibility) was simulated using LOWTRAN-6 (Kneizys et al., 1983).

The second step integrated bidirectional reflectance distribution factors over the hemisphere surrounding reflecting surfaces (Kimes and Sellers 1985). The product of the mean bidirectional reflectance factors for each view direction and the projected solar angle is then summed over the eight solid angles to compute albedo.

The "true" albedos of big bluestem were derived using all of the available bidirectional reflectance data. Albedos were also estimated using subsets of data from combinations of two orthogonal planes and data from single azimuthal planes. One combination of two planes consisted of the principal plane and the plane perpendicular to the principal plane. The other combination consisted of the two planes which form 45^{o} angles with the principal plane. Albedos derived from subsets of the data were compared to "true" albedos derived from the full data sets.

Results and Discussion

Albedo of big bluestem increased with solar zenith angle on each date (Table 1). For nearly equal solar zenith angles, albedos increased from 3 June to 17 June and remained nearly constant until 3 July. The one albedo estimate available for 12 August indicated that big bluestem albedo decreased at this stage of the growing season. From 3 June to 3 July the grass grew rapidly. Green leaf area index (GLAI) increased from 3.1 to 5.8 and plant height increased from 0.3 at tillering to 1.2 at anthesis (Table 2).

Table 1 also lists relative errors in albedo induced by using subsets of the data. Albedo estimates derived from data taken along two orthogonal azimuthal planes were within 3% of the "true" albedo at all solar zeniths. Albedo estimates derived from only a single plane produced the large errors particularly at large solar zenith angles. For example, at solar zenith angles greater than 25^{o}, albedos derived from data along the principal plane overestimated "true" albedo while estimates derived from data along the perpendicular plane underestimated "true" albedo. Albedos derived from nadir bidirectional reflectance measurements only had the largest errors.

Table 1. Albedos for big bluestem grass during growing season. Albedos are derived by numeric integration of data from various combinations of azimuthal planes and from nadir reflectance. Percent difference is the albedo predicted with a subset of the data minus the "true" albedo divided by "true" albedo.

Date	Solar Az	Solar Zen	"True" Albedo	Percent Difference† P+P	+45	Prin	Perp	Nadir
	degrees		%	- - - - - -	-	% - - - - -	-	-
3 June	181	18	22.2	-1.5	1.5	-3.6	0.6	-0.4
	99	45	26.5	-0.9	0.9	4.2	-6.0	-18.1
17 June	185	17	26.5	-0.4	0.3	-3.1	2.3	-0.4
	231	24	27.4	-0.2	0.2	-0.4	0.1	-6.1
	265	47	31.5	-1.1	1.1	6.0	-8.1	-7.2
	274	57	34.6	-0.8	0.8	7.1	-8.6	-11.5
	283	68	37.6	-2.6	2.6	11.2	-16.4	-10.8
3 July	231	25	28.5	-0.1	0.1	0.7	-1.0	-2.5
	282	68	37.7	-1.0	1.0	6.8	-8.8	-16.2
12 Aug	135	33	21.7	-0.7	0.7	2.3	-3.4	-12.3
RMS Difference				1.1	1.1	5.5	7.3	10.4
n			75	30	30	15	15	4

† The subsets of the data used to estimate albedo are as follows:

P+P = principal plane plus plane perpendicular to principal plane of sun;
±45 = plus and minus 45° of principal plane of sun;
Prin. = principal plane of sun;
Perp = plane perpendicular to principal plane of sun;
Nadir = nadir observations only ($\theta_v = 0$; $\phi_v = 0$).

Table 2. Phytomass and leaf area index (LAI) of big bluestem grass during 1986. Values are means of five 0.1 m^2 samples.

Date	Fresh Phytomass	Dry Phytomass† Total	GL	BL	Stems	GLAI	SAI	Height
	g m^{-2}	- - - - g m^{-2} - - -						m
4 June	1302	253	148	0	104	3.1	0.2	0.3
19 June	1837	394	247	14	133	4.9	0.6	0.6
7 July	2248	653	381	72	200	5.8	0.6	1.2
14 Aug	2207	854	237	243	375	2.3	0.7	1.2

† GL = Green Leaf dry weight; BL = Brown Leaf dry weight; GLAI = Green Leaf Area Index and is the area of one side of all green leaves per unit area of soil. SAI = Stem Area Index and is the vertical projection of area of all stems (culms) per unit area of soil.

At small solar zenith angles (e.g., 18^o), the reflectance of big bluestem is relatively isotropic for all view directions. At larger solar zenith angles reflectance increases off nadir. When bidirectional reflectance is integrated over all view directions to compute albedo, the increase in off-nadir reflectance at larger solar zeniths results in larger albedos relative to the albedos at the smaller solar zenith.

The effect of solar zenith on big bluestem albedo may be attributed to the orientation of big bluestem leaves relative to the solar direction. The grass appears to trap and utilize more of the available solar energy when the sun is high than when the sun is low. Since the solar flux density is proportional to the cosine of the solar zenith, perhaps the big bluestem canopy geometry evolved in a manner which maximizes the use of the solar energy available over a day.

The results of this study indicate that bidirectional reflectance measurements must be taken along at least two azimuthal planes to accurately estimate the albedo of the grasslands. Neither a single nadir observation nor a sequence of observations along a single plane are adequate for accurate estimation of albedo. A single nadir measurement would only provide a suitable estimate of albedo at a small solar zenith angle when the BRDF of the big bluestem prairie grass is relatively isotropic.

References

Eaton, F.D., and I. Dirmhirn. 1979. Reflectance irradiation indicatrices of natural surfaces and their effect on albedo. Applied Optics 18:994-1008

Kimes, D.S., and P.J. Sellers. 1985. Inferring hemispherical reflectance of the earth's surface for global energy budgets from remotely sensed nadir of directional radiance values. Remote Sensing of Environment, 18:205-223.

Kneizys, F.X., 1983. Atmospheric transmittance/radiance: computer code LOWTRAN 6. Environmental Research Papers, No. 846. Optical Physics Division, Air Force Geophysics Laboratory, Hanscom AFB, Ma.

Irons, J.R., B.L. Johnson, Jr., and G.H. Linebaugh. 1987. Multiple-angle observations of reflectance anisotropy from an airborne linear array sensor. IEEE Transactions on Geoscience and Remote Sensing. (in press).

Ranson, K.J., L.L. Biehl, and M.E. Bauer. 1985a. Variation in spectral response of soybeans with respect to illumination, view and canopy geometry. International Journal of Remote Sensing, 6:1827-1842.

Ranson, K.J., C.S.T. Daughtry, L.L. Biehl, and M.E. Bauer. 1985b. Sun-view angle effects on reflectance factors of corn canopies. Remote Sensing of Environment, 18:147-161.

Robinson, B.F. and L.L. Biehl. 1979. Calibration procedures for measurement of reflectance factor in remote sensing field research. Proc. Society Photo-Optical Instrumentation Engineering 196:16-26.

Sellers, P.J. and F.G. Hall. 1987. The FIFE experiment plan. NASA/GSFC Earth Resources Branch, Greenbelt, MD 20771.

Walthall, C.L., J.M. Norman, J.M. Welles, G. Campbell, and B.L. Blad. 1985. Simple equation to approximate the bidirectional reflectance from vegetative canopies and bare soil surfaces. Applied Optics, 24:383-387.

Wiesnet, D.R., and M. Matson. 1983. Remote sensing of weather and climate. _in_ Manual of Remote Sensing, Second Edition, Volume II. J.E. Estes and G.A. Thorley, eds. American Society of Photogrammetry, Falls Church, VA.

III. PUBLICATIONS

The following list of papers, reports, and abstracts represents the results of research wholly supported or at least partially supported by this NASA grant. These informal jointly sponsored research efforts resulted when several investigators with similar interests collaborated to maximize the use of available resources and to most effectively achieve their own objectives.

Brooks, C. C., and C. S. T. Daughtry. 1987. Indirect estimation of leaf area index of soybeans. (manuscript for Agronomy Journal)

Daughtry, C. S. T. and K. J. Ranson. 1986. Assessing vegetation characteristics with multispectral data. Amer. Soc. Agric. Engineers. Winter Meeting, Chicago, IL. 16-19 Dec. 1986, Paper no. 86-3514.

Daughtry, C. S. T. and K. J. Ranson. 1987. Assessing vegetation characteristics with multispectral data. (Submitted to Remote Sensing of Environment).

Gallo, K. P. and C. S. T. Daughtry. 1986. Effects of spectral waveband selection on vegetation indexes of corn canopies. Agron. Abstr. 78:13.

Gallo, K. P. and C. S. T. Daughtry. 1987. Differences in vegetation indices for the Landsat-5 MSS and TM, NOAA-9 AVHRR, and SPOT-1 Sensor Systems. Remote Sens. Environ. (accepted).

Irons, J. R., K. J. Ranson, and C. S. T. Daughtry. 1987. Estimating big bluestem albedo from directional reflectance measurements. (submitted to Remote Sensing of Environment)

Star Information Form

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Estimating Scattered and Absorbed Radiation in Plant Canopies by Remote Sensing		5. Report Date July 1987 6. Performing Organization Code
7. Author(s) C. S. T. Daughtry and K. J. Ranson		8. Performing Organization Report No. LARS 071587
9. Performing Organization Name and Address Laboratory for Applications of Remote Sensing 214 Entomology Building Purdue University West Lafayette, IN 47907		10. Work Unit No. 11. Contract or Grant No. NAG5-771
12. Sponsoring Agency Name and Address NASA Goddard Space Flight Center Code 623 Greenbelt, MD 20771		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code
15. Supplementary Notes Forrest G. Hall, Technical Monitor C. S. T. Daughtry, Principal Investigator		

16. Abstract

This document is the final report of the research results and accomplishments for Grant NAG-5-771, "Estimating Scattered and Absorbed Radiation in Plant Canopies by Remote Sensing". Much of this research has been or soon will be published in scientific journals.

This report is divided into three sections including this introduction. In Section II we present three synopses which describe our significant research accomplishments during this grant. The first synopsis reviews the relationships of canopy characteristics to multispectral reflectance factors of vegetation and discusses several alternative approaches for incorporating spectrally-derived information into plant models. In the second synopsis we describe and evaluate a method to estimate leaf area index from measurements of radiation transmitted through plant canopies. In the third synopsis we estimate albedo of a big bluestem grass canopy from 60 directional reflectance factor measurements and evaluate effects of estimating albedo with substantially smaller subsets of these data. These data for big bluestem that we acquired in 1986 are available to other researchers upon request.

In Section III we list the publications (both actual and anticipated) that were at least partially supported by this grant. For a more complete discussion of each of accomplishments described in Section II, please refer to these publications.

17. Key Words (Suggested by Author(s)) Field research, reflectance factor, albedo, high interception	18. Distribution Statement List included on back cover.

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

*For sale by the N[illegible]nal Technical Information Service, Springfield, Virginia 22161

NASA - JSC