Final Report

Measuring and Modeling Biophysical and Optical Properties of Diverse Vegetative Canopies

by

C. S. T. Daughtry
K. J. Ranson
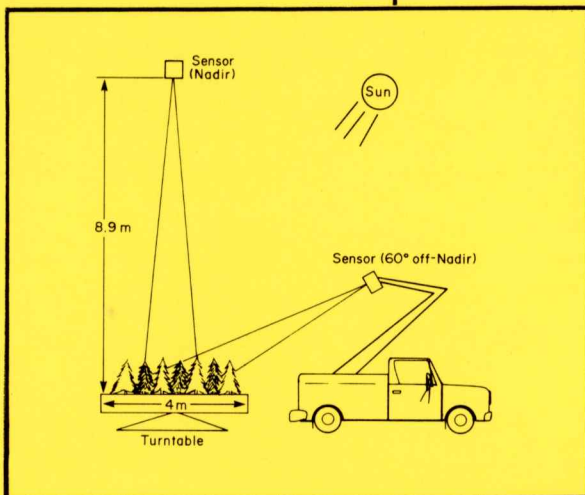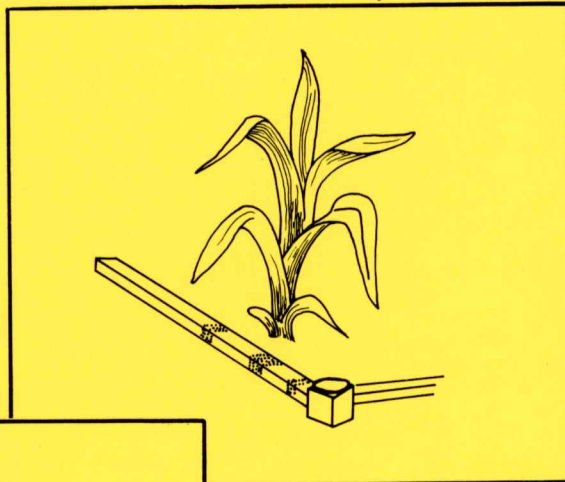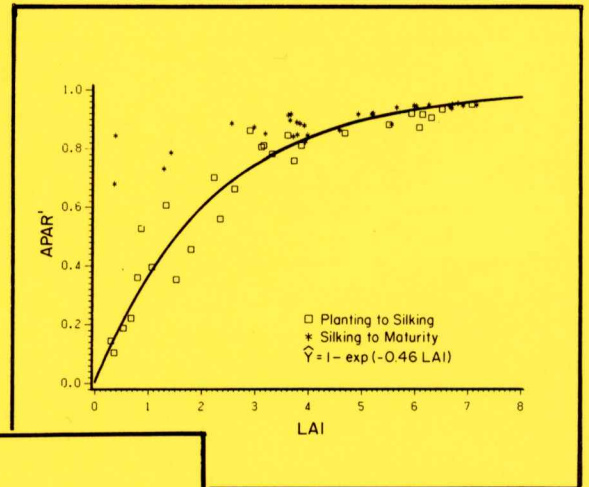
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Laboratory for Applications of Remote Sensing
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16. Abstract

This report presents the research results and accomplishments for Contract NAS9-16528, "Remote Sensing of Agricultural Crops and Soils: Measuring and Modeling Biophysical and Optical Properties of Diverse Vegetative Canopies", at Purdue University, West Lafayette, Indiana from January 1983 through April 1986. Much of this research has been published or will soon be published in scientific journals.

This report is divided into five major sections including this introduction. In Section II we present a series of 18 synopses which describe our significant research accomplishments. Our major contributions of technical assistance provided to various NASA/Johnson Space Center projects are succinctly summarized in Section III. In the fourth section we list 27 refereed papers, 12 technical reports, 4 conference papers, 12 published abstracts, and 9 theses that were prepared by the staff at Purdue during this contract. The fifth and final section lists 32 publications by other researchers who have used spectral and ancillary (i.e., agronomic, biological, physical, and meteorological) data acquired by the staff at Purdue University.

Research in four major areas is described: (1) sun and view angle effects on canopy reflectance, (2) development of new measurement techniques, (3) spectral measurements of intercepted radiation, and (4) measurements of phytomass, leaf area index, and stage of development. Detailed information describing the various tasks, experiments, and results are available in the synopses in Section II and in the published scientific papers and technical reports listed in sections IV and V.

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I. INTRODUCTION

This document is the final report of the research results and accomplishments for Contract NAS9-16528, "Remote Sensing of Agricultural Crops and Soils: Measuring and Modeling Biophysical and Optical Properties of Diverse Vegetative Canopies", at Purdue University, West Lafayette, Indiana from January 1983 through April 1986. Much of this research has been published or will soon be published in scientific journals.

This report is divided into five major sections including this introduction. In Section II we present a series of 18 synopses which describe our significant research accomplishments. Our major contributions of technical assistance provided to various NASA/Johnson Space Center projects are succinctly summarized in Section III. In the fourth section we list 27 refereed papers, 12 technical reports, 4 conference papers, 12 published abstracts, and 9 theses that were prepared by the staff at Purdue during this contract. The fifth and final section lists 32 publications by other researchers who have used spectral and ancillary (i.e., agronomic, biological, physical, and meteorological) data acquired by the staff at Purdue University.

Research was conducted in four major areas: (1) sun and view angle effects on canopy reflectance, (2) development of new measurement techniques, (3) spectral measurements of intercepted radiation, and (4) measurements of phytomass, leaf area index, and stage of development. Briefly our most significant research accomplishments during this contract include:

* Characterization (measuring, analyzing, and modeling) of the spectral properties of corn, soybeans and balsam fir canopies with respect to illumination and viewing geometries. The effects of sun and view angles on vegetation indices were also described and evaluated. Comprehensive sets of bidirectional reflectance data and biophysical data describing the canopies were assembled and distributed to scientists around the world. The known publications derived from these data are listed.

* Development and testing of new techniques to measure (i) absorbed and intercepted photosynthetically active radiation in crop canopies, (ii) diffusive resistance of leaves from remotely sensed data, (iii) spectral properties of conifer needles, and (iv) changes in the spectral properties of leaves during senescence. Additional research focused on describing the two-dimensional orientation of leaves, on evaluating the costs of measuring leaf area index directly and on sampling the spectral variability of aspen leaves.

* Estimation of intercepted and absorbed radiation and leaf area index from multispectral measurements of corn and soybean canopies. Seasonal cummulations of intercepted radiation were highly correlated with grain yields in both crops.

* Determination of relationships between spectral reflectance and biophysical characteristics, such as leaf area index, phytomass and percent cover, of corn soybeans and wheat. Two new terms, leaf chlorophyll density and leaf total N density, were defined and were shown to be highly related to multispectral reflectance. Models for estimating stages of development of corn for large areas were also developed and tested.

Additional detailed information describing the various tasks, experiments, and results are available in the synopses in Section II and in the published scientific papers and technical reports listed in sections IV and V.

II. SIGNIFICANT ACCOMPLISHMENTS

A. Sun and View Angle Effects on Canopy Reflectance

A.1. Sun angle, view angle and background effects on spectral response of balsam fir canopies.
K. J. Ranson, C. S. T. Daughtry, and L. L. Biehl

An experiment is described that examines the effects of solar zenith angle and background reflectance on the composite scene reflectance of small balsam fir (Abies balsamea (C.) Mill.) arranged in different densities. Visible, near-infrared and middle infrared reflectance factors were measured at 0 and 60° view zenith angle through a range of solar zenith angles (Fig. A1.1). In this study, the shape, density, and consequently the needle area index and phytomass of the canopies, as well as the background reflectance, were controlled.

The effects of sun angle, view angle, and background reflectance on the multispectral response of small balsam fir trees varied for normalized difference (ND) (Fig. A1.2) and greenness (GR) (Fig. A1.3) vegetation indices. Regression models relating spectral vegetation indices (ie., normalized difference (ND) and greenness (GR) to phytomass showed very poor relationships for balsam fir canopies with a grass background (Table A1.1). However, strong linear relationships were found for ND (R^2 = 0.9) and GR (R^2 = 0.8) with phytomass for a background that simulated the reflectance of snow. Changing solar zenith angle significantly affected the models relating ND to phytomass for the snow background, but was not significant in the model relating GR to phytomass for the snow background.

The spectral properties of the background may confound changes in the spectral response of the trees. Our results suggest winter-time data, when snow masks the understory, would provide better estimates of overstory phytomass in coniferous forests than summer-time data.
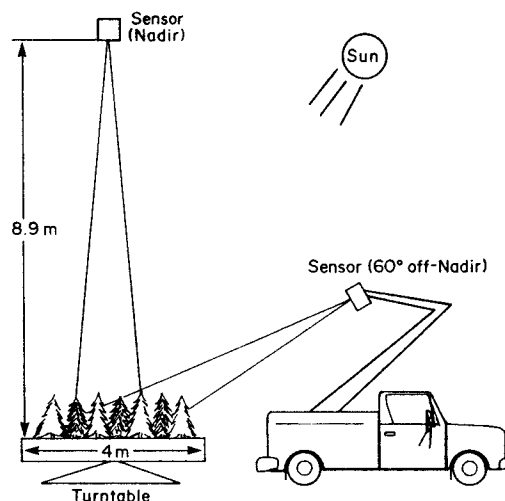
Figure A1.1 Arrangement of sensors for balsam fir turntable experiment.

Table A1.1. Multiple regression coefficients for relationships of normalized difference (ND) and greenness (GR) to phytomass (X) and solar zenith angle (θ_S). Model used was $Y = b_0 + b_1 X + b_2 \theta_S$.

Spectral Variable	b_0	b_1	b_2	R^2	SE_1	SE_2
			Grass			
ND	0.78^{**}	0.007	0.001^{**}	0.36	0.005	0.0003
GR	45.97^{**}	-0.544^*	-0.087^{**}	0.28	0.406	0.024
			"Snow"			
ND	-0.15^{**}	0.274^{**}	0.005^{**}	0.92	0.015	0.001
GR	10.62^{**}	10.790^{**}	0.074	0.82	0.957	0.055

** Coefficient significant at $\alpha = 0.01$.
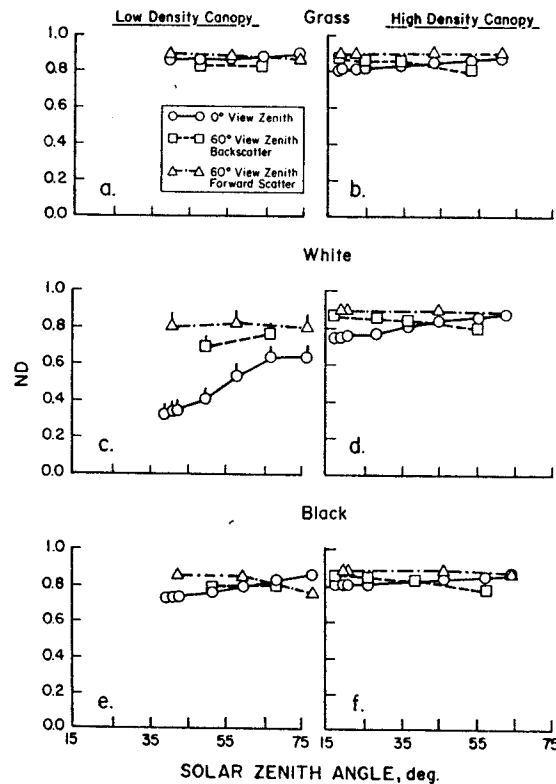
Figure A1.2. Mean normalized difference (ND) variation with solar zenith angle for low and high density balsam fir canopies with different backgrounds and sensor view geometries. Vertical bars indicate one standard deviation.
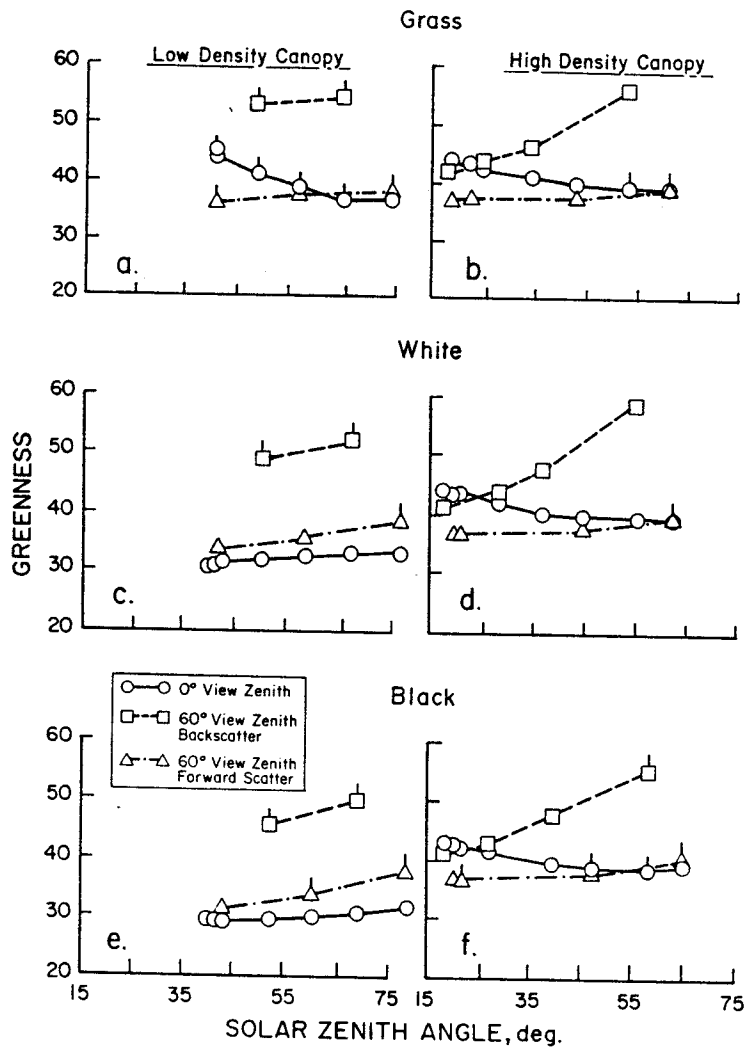
Figure A1.3. Mean Greenness (GR) variation with solar zenith angle for low and high density balsam fir canopies with different backgrounds and sensor view geometries. Vertical bars indicate one standard deviation.

A.2 Scene Shadow Effects of Multispectral Response
      K. J. Ranson and C. S. T. Daughtry

The behavior of canopy reflectance and spectral band transform-
ations normalized difference (ND) and greenness (GR) due to the amount
and location of scene shadows was examined. Live balsam fir (<u>Abies</u>
<u>balsamea</u> L. (Mill.)) trees were arranged in an equidistant pattern on a
platform. Spectral reflectances were acquired for three canopies (44,
70 and 90 percent cover) and three background types (grass-sod, black-
and white-painted boards) for a range of solar zenith angles. Rotating
the platform produced variations in the location of shadows cast by
trees in the scene as illustrated in Fig. A2.1.
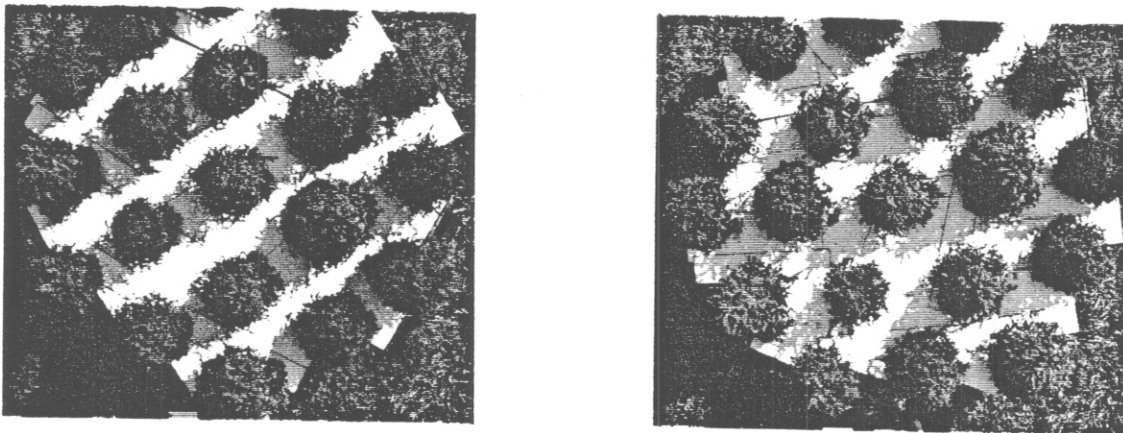
Figure A2.1. Shadow patterns in the scene varied as the turntable was
rotated.

Red and near-IR RFs decreased as the amount of scene shadows
increased while ND increased with increasing scene shadows. In Figure
A2.2 the spectral response is shown for balsam fir with the white
background as the turntable was rotated in 10° increments. The
oscillating pattern noted for red, near-ir and ND data was the result of
changing shadow patterns in the scene. When large amounts of green
vegetation were present ND saturated and the observed increases were
reduced as shown in Figure A2.3 for the balsam fir with grass
background. GR was least affected by changing shadow amounts. Spectral
response variations due to shadows decreased as canopy cover increased.

A simple model was used to examine the effects of shadows in
"pure" pixels of backgrounds representing vegetation, bare soil and
snow. Red and near-infrared reflectance decreased and ND increased as
the proportion of shadows increased (Fig. A2.4). These results suggest
that green vegetation phytomass may be over estimated by ND when shadows
cast by vegetation are present in a scene.
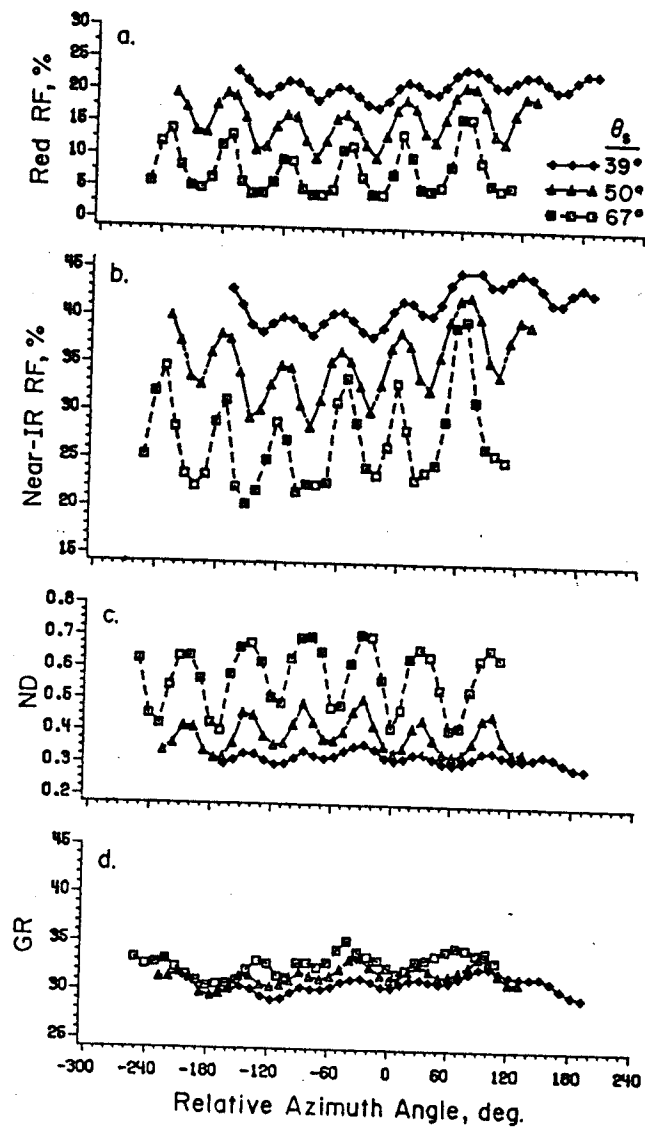
Figure A2.2. Variation of spectral response with relative azimuth angle (turntable angle-solar azimuth angle) and solar zenith angle for low density canopy and white background. a) red band RF, b) near-IR RF, c) normalized difference (ND) and d) greenness (GR).
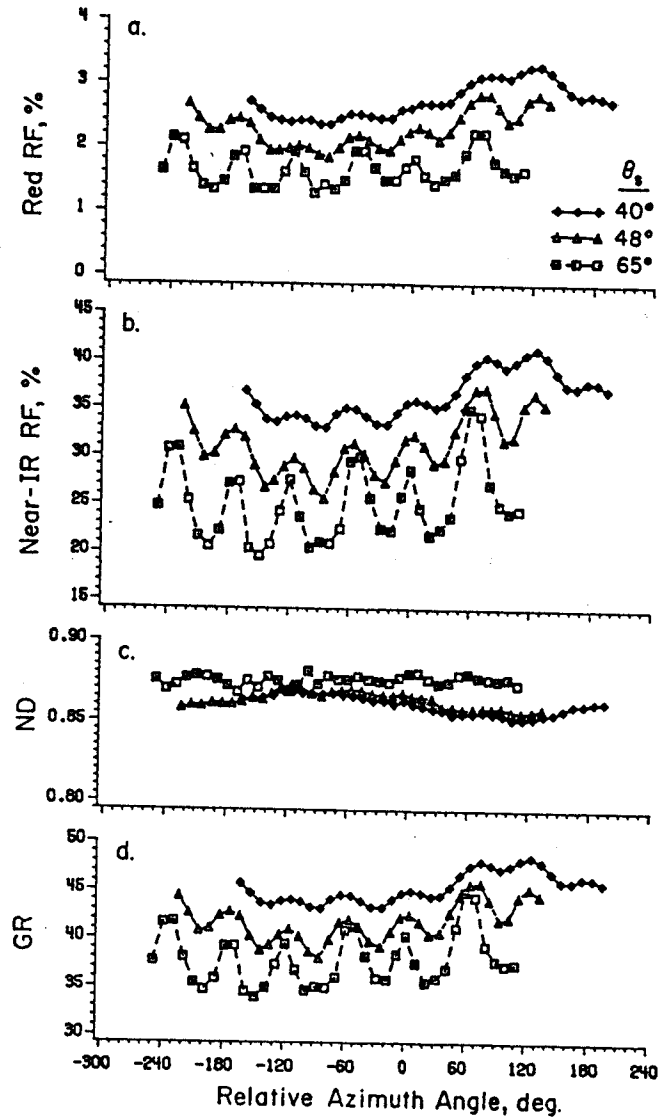
Figure A2.3. Variation of spectral response with relative azimuth angle (turntable angle-solar azimuth angle) and solar zenith angle for low density canopy and grass background. a) red band RF, b) near-IR RF, c) normalized difference (ND) and d) greenness (GR).
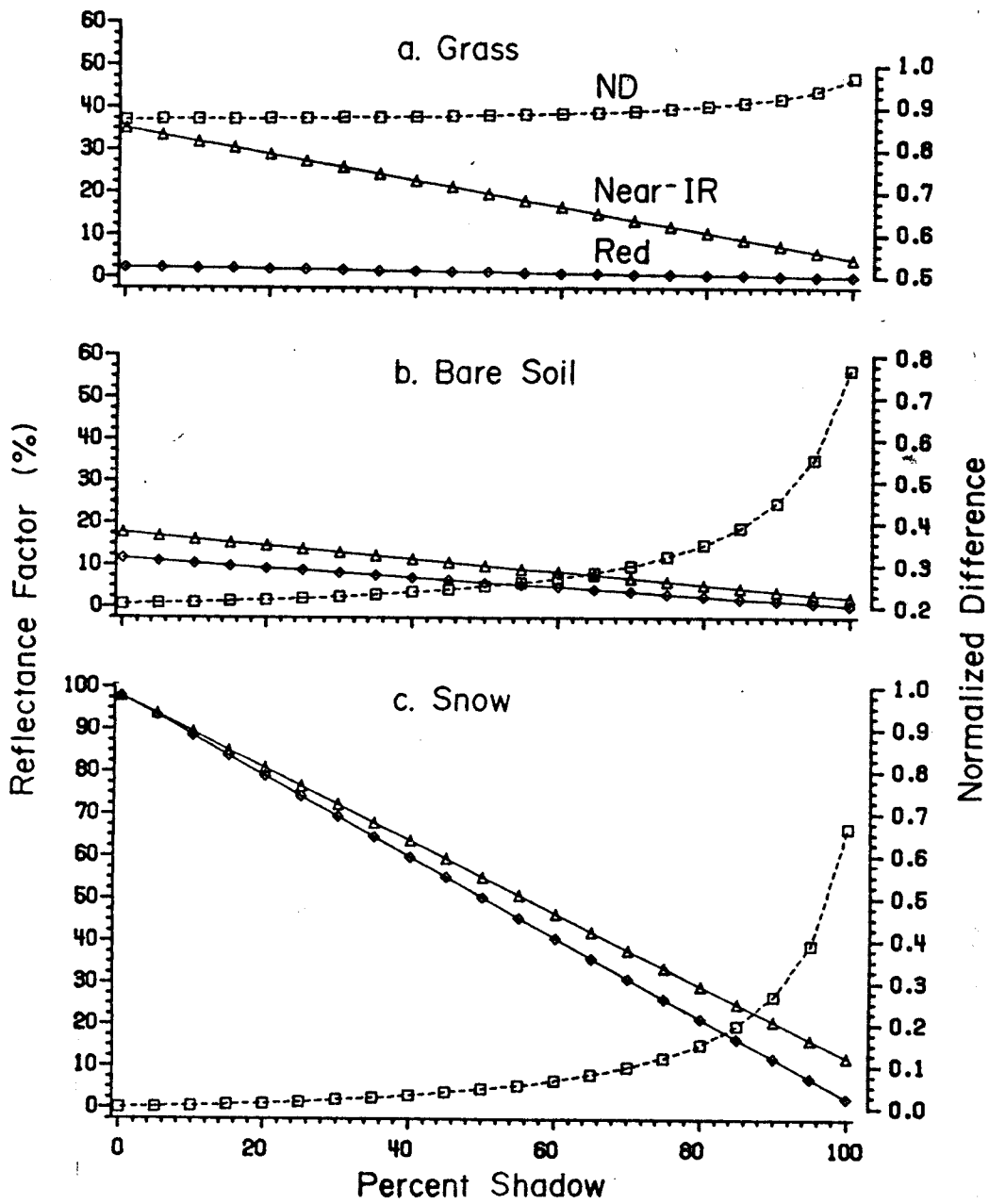
Figure A2.4. Calculated red, near-IR RFs and normalized differences (ND) for three background types as shadows increased from 0 to 100%.

A.3. Variation in spectral response of soybeans with respect to
      illumination, view and canopy geometry
        K. Jon Ranson and Larry L. Biehl and Marvin E. Bauer

        Comparisons of the spectral response for incomplete (well-defined
row structure) and complete (overlapping row structure) soybean canopies
indicated that there was a greater dependence on sun and view geometry
for the incomplete canopies. This effect was more pronounced for the
highly absorptive red (0.6-0.7 μm) wavelength band than for the near-
infrared (IR) (0.8-1.1 μm) based on relative reflectance factor changes.

        Red and near-IR reflectance for the incomplete canopy decreased as
solar zenith angle increased for a nadir view angle until the soil
between the plant rows was completely shaded (Fig A3.1). Thereafter for
increasing solar zenith angle the red reflectance leveled off and the
near-IR reflectance increased.
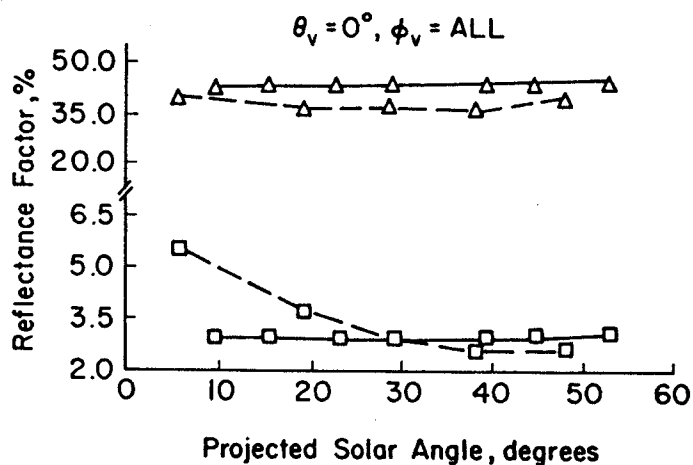
Figure A3.1. Relationship of nadir acquired reflectance factors with
projected solar angle for incomplete and complete soybean canopies.
Dashed and solid lines represent incomplete and complete canopies,
respectively. Squares and triangles indicate red (0.6-0.7μm) and near-
IR (0.8-1.1μm) wavelength bands respectively. Standard deviations were
less than or equal to symbol height.

A 'hot-spot' effect was evident for the red and near-IR reflectance factors, especially when the sun and view directions were perpendicular with the rows. The 'hot-spot' effect was more pronounced for the red band based on ratios of off-nadir to nadir reflectances (Fig. A3.2). The normalized difference vegetation index (ND) was least affected by viewing angles when amount of sunlit soil was minimized. The effect of solar zenith angle was more pronounced for view angles perpendicular to the row direction.
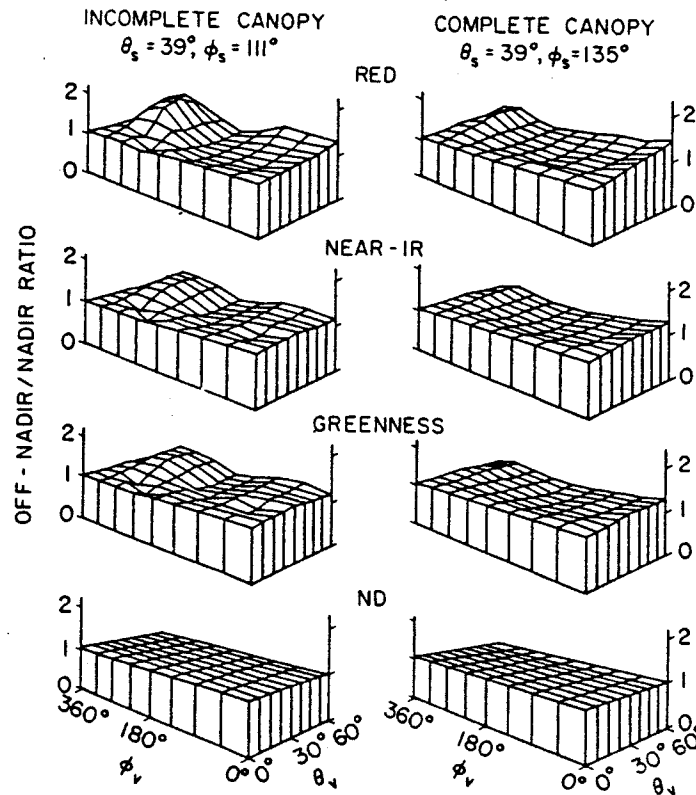
Figure A3.2. Response surface plots of ratios of off-nadir to nadir reflectance for incomplete and complete soybean canopies with view zenith (θ_V) and view azimuth (ϕ_V) angles. Data acquired in mid-morning.

An analysis of the ratios of off-nadir to nadir-acquired data also revealed that off-nadir red band reflectance factors more closely approximated straight-down measurements for time periods away from solar noon. Near-IR and greenness responses showed a similar behavior. Normalized difference generally approximated straight-down measurements during the middle portion of the day. An exception occurred near solar noon when sunlit bare soil was present in the scene.

A.4.   Sun-view angle effects on reflectance factors of corn canopies.
       K. J. Ranson, C. S. T. Daughtry, L. L. Biehl, and M. E. Bauer

The bidirectional reflectance characteristics of vegetation
canopies vary with time of day and through the growing season.   In this
study the effects of sun and view angles on bidirectional reflectance
factors from corn (Zea mays L.) canopies ranging in development from the
six leaf stage to harvest maturity were examined.   Reflectance factors
were acquired from a 10 m tower (Fig. A4.1) for view zenith angles
ranging from 0° to 70° and view azimuths every 45° from 0 to 360°.

Figure A4.1.   Reflectance factors were measured at many angles from the
top of a 10 m tower.

For nadir-acquired reflectance factors there was a strong solar
angle dependence in all spectral bands for canopies with low leaf area
index (LAI) (Fig. A4.2).   A decrease in contrast between bare soil and
vegetation due to shadows at larger solar zenith angles appeared to be
the cause of this dependence.   Sun angle dependence was least for well-
developed canopies with higher LAI.   However, for higher LAI canopies a
moderate increase in reflectance factor was observed at larger solar
zenith angles and was attributed to the presence of specular
reflectance.

Spectral measurements acquired through 70° view zenith angle for
different stages of canopy development demonstrated the variation in
magnitude and trend of spectral reflectance factors for phenologically
different canopies (Fig. A4.3).   Trends of off-nadir reflectance factors
with respect to sun angle at different view azimuth angles indicated
that the position of the sensor relative to the sun was an important
factor for determining the angular reflectance characteristics of corn
canopies.   Reflectance factors were maximized for coincident sun and
view angles and minimized when the sensor view direction was towards the
sun.   View direction relative to row orientation also contributed to the
variation in reflectance factors.
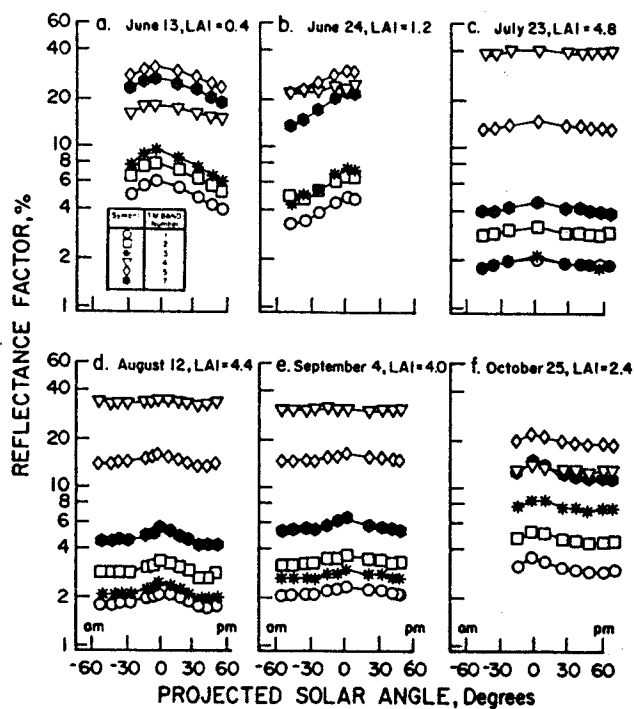
Figure A4.2. Nadir reflectance factors plotted as a function of projected solar angle for corn canopies at six stages of development. Spectral band numbers are noted in legend. Standard deviations were less than or equal to symbol height.
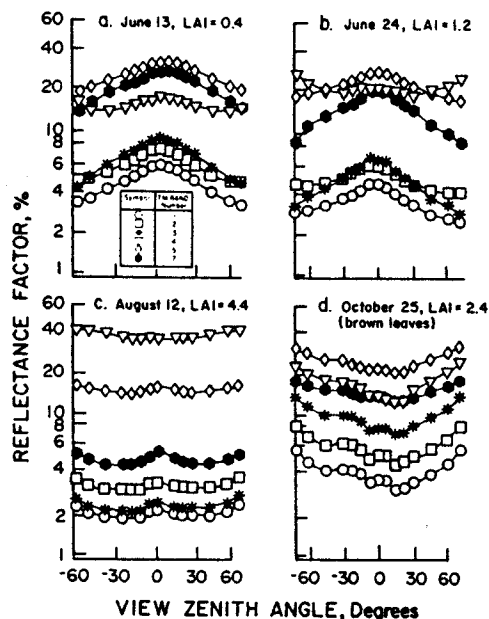
Figure A4.3. Relationship of reflectance factors with view zenith angle for sparse (a and b), well developed (c) and senescent (d) corn canopies from data acquired near solar noon. Negative and positive view zenith angles indicate that the radiometer was looking east, (ϕ_V=90°) and west (ϕ_V=270°), respectively. TM band numbers are noted in the legend.

B. Development of New Measurement Techniques

B.1. Techniques for Measuring Intercepted and Absorbed Photosynthetically Active Radiation in Corn Canopies
K. P. Gallo and C. S. T. Daughtry

A portable system that would enable rapid measurement of photosynthetically active radiation (PAR) would be useful in studies that include measurements of interception and absorption of PAR in crop canopies. The objectives of this study were to develop and evaluate a portable system for measuring intercepted and absorbed PAR in corn (Zea mays L.) canopies.

This study consisted of two field experiments with corn planted in north-south rows at two densities with two planted dates in each of 2 years. The soil was a dark (10YR 4/1) Chalmers silt loam (Typic Argiaquoll). A handle, two levels, and a data logger were added to a line quantum sensor (Fig. B1.1) to form a portable system for rapidly measuring the ascending and descending fluxes associated with absorbed PAR (APAR).

The effects of sensor orientation and surface length on measurement of transmitted PAR and the errors induced by use of intercepted PAR as an estimate of absorbed PAR were examined. Transmitted PAR (TPAR) was optimally measured with the sensor leveled and positioned perpendicular to the row direction with the length of the sensor equal to the row spacing. Transmitted PAR decreased rapidly from a maximum of 100% at planting to a minimum of < 15% at 65 days after planting (silking, R1) and then increased as the canopies senesced (Fig. B1.2). Intercepted PAR (IPAR), the difference in descending PAR fluxes above and below the canopy required fewer measurements than APAR and differed from APAR by the difference between canopy and soil surface reflectances (Table B1.1). Prior to the dent stage (R5) of grain maturity, differences between APAR and IPAR were less than 3.5% for this study. Thus IPAR was a reasonable approximation of APAR and required fewer measurements.

Figure B1.1. The modified line quantum sensor used in this study.
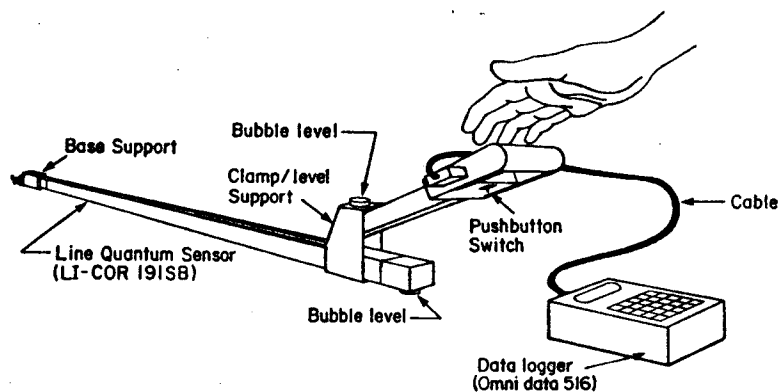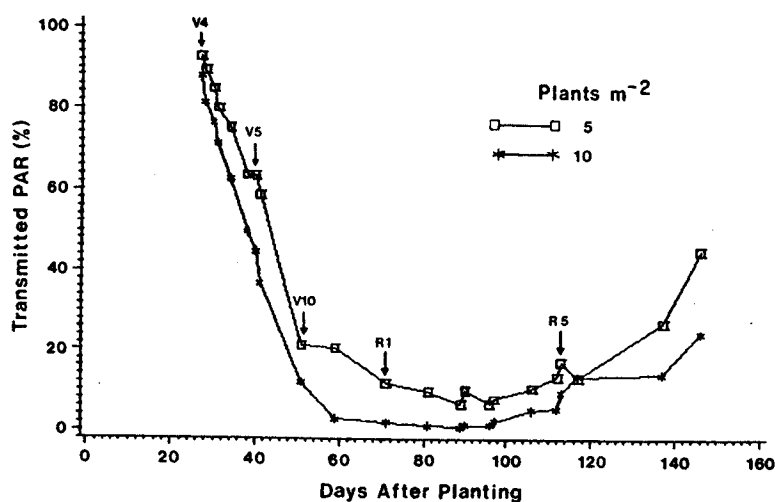
Figure B1.2. Transmitted PAR plotted as function of days after planting
for observations of the 14 May 1982 planting of corn. Standard
deviations of transmitted PAR are less than the width of the symbols
used to represent the mean values.

Table B1.1. The percentages of incident PAR that were reflected by the
soil ($RPAR_S$) and canopy surfaces ($RPAR_C$), transmitted (TPAR),
intercepted (IPAR) and absorbed (APAR) by corn canopies of two planting
densities in 1982. Data were acquired within 0.5 h of solar noon.

Stage	LAI	$RPAR_S$	$RPAR_C$	TPAR	IPAR	APAR	Error
				%			
5 plants m^{-2}							
V6	0.6	7.4	6.2	79.9	20.1	21.3	-1.2
V14	3.6	1.9	2.9	20.5	79.5	78.5	1.0
VT	3.9	1.1	3.2	11.7	88.3	86.2	2.1
R5	0.0	3.5	5.9	37.3	62.7	60.3	2.4
10 plants m^{-2}							
V6	0.9	6.6	5.2	71.2	28.8	30.2	-1.4
V14	6.8	0.3	3.0	3.0	97.0	94.3	2.7
VT	6.5	0.2	3.1	2.2	97.8	94.9	2.9
R5	0.0	2.4	6.4	25.8	74.2	70.2	4.0

Error = (IPAR - APAR) = ($RPAR_C$ - $RPAR_S$)

B.2. A New Method for the Estimation of Diffusive Resistance of Leaves[*]
K. T. Paw U and C. S. T. Daughtry

The measurement of diffusive resistance in leaves is a difficult task, and is frequently accomplished with diffusion porometers. A new energy budget method is shown, where the internal diffusive resistance, the aerodynamic resistance, and the absorbed radiation may be estimated using the temperature of three leaves, the air temperature, and the relative humidity or vapor pressure deficit. Of the three leaves, one is coated with a substance impervious to water(i.e., no latent energy exchange), one with water (i.e., free water evaporation), and one is left uncoated (i.e., normal).

The spectral spectral properties of coated and uncoated leaves are shown in Figures B2.1 and B2.2. Absorbed solar irradiances in the 400 to 1100 nm wavelength region for coated leaves were within 2% and 6% of uncoated leaves for adaxial (upper) and abaxial (lower) surfaces, respectively (Table B2.1). The methodology was tested on soybean plants with diffusion porometry used as a reference. The results showed a good correspondence between the two methods, with only as much scatter as reported in inter-porometer comparisons (Fig B2.3). The method presented here may be developed for automatic unattended operation.

Table B2.1 Hemispherical radiance reflected, transmitted, and absorbed by the adaxial and abaxial surfaces of uncoated (normal) and water- and jelly-coated soybean leaves.

	Radiance[a]			Difference[b]		Rel. Change[c]	
	Uncoated	Water	Jelly	Water	Jelly	Water	Jelly
	- - - ($W\ m^{-2}$) - - -			- ($W\ m^{-2}$) -		- - (%) - -	
	Adaxial Surface						
Reflected	209.4	199.9	209.7	-9.5	0.3	-4.5	0.1
Transmitted	183.9	193.5	189.8	9.6	5.9	5.2	3.2
Absorbed	450.8	50.7	444.7	-0.1	-6.1	-0.0	-1.4
	Abaxial Surface						
Reflected	211.9	202.9	235.1	-9.0	23.2	-4.2	10.9
Transmitted	200.6	214.0	202.8	13.4	2.2	6.7	1.1
Absorbed	431.6	427.2	406.2	-4.4	-25.4	-1.0	-5.9

[a] Spectral radiant exitance integrated over the 400 to 1100 nm wavelength region.
[b] Radiance of coated leaf minus radiance to uncoated leaf.
[c] Relative change in radiance is difference divided by radiance of uncoated leaf.
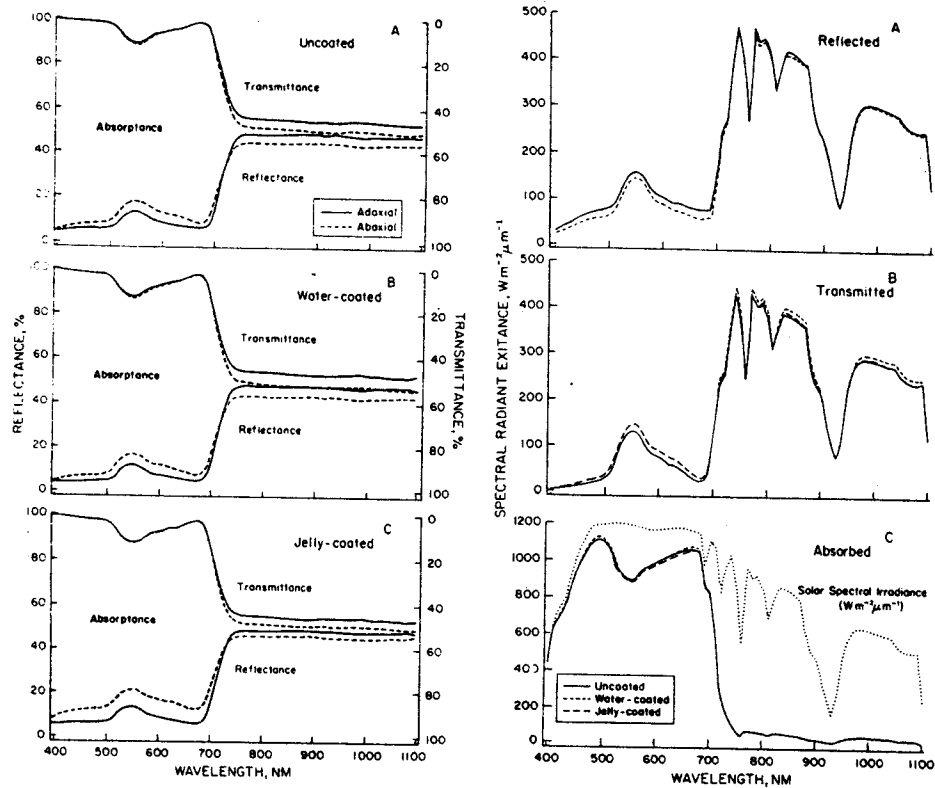
Figure B2.1.(left)   Reflectance, transmittance and absorptance spectra of coated and uncoated soybean leaves.   Data are means of two leaves.

Figure B2.2.(right)   Spectral radiant exitance reflected, transmitted, and absorbed by adaxial surface of coated and uncoated soybean leaves. Spectral irradiance of solar radiation at sea level is included.

Figure B2.3   Linear plot of energy budget-derived diffusive resistance vs. transient diffusion porometer-derived resistance.   One to one line is shown.
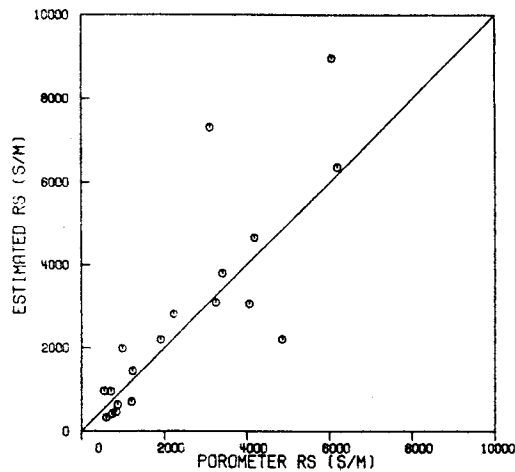
B.3. Costs of measuring leaf area index of corn.
C. S. T. Daughtry and S. E. Hollinger

Leaf area index (LAI) is an important biophysical parameter of crop canopies. Accurate measurements of LAI are laborious and time-consuming. Many methods of measuring LAI of corn (Zea mays L.) have been reported and vary greatly in their accuracy, precision, bias, and ease of measurement.

We examined the magnitude of plant-to-plant variability of leaf area of corn plants selected from uniform plots (Table B3.1) and evaluated four representative methods for measuring LAI (Table B3.2). The number of plants required and the relative costs for each sampling method were calculated to detect 10, 20, and 50% differences in LAI using 0.05 and 0.01 tests of significance and a 90% probability of success ($\beta = 0.1$).

The natural variability of leaf area per corn plant was nearly 10%. Additional variability or experimental error may be introduced by the measurement technique employed and by nonuniformity within the plot (Table B3.1). Direct measurement of leaf area with an electronic area meter had the lowest coefficient of variation (CV), required that the fewest plants be sampled, but required approximately the same amount of time as the leaf area/weight ratio method. Measurements of length and width of leaves required more plants, but less total time than the direct method (Table B3.3). Unless the coefficients for converting length and width to area are verified frequently, the indirect methods may be biased.

When true differences in LAI among treatments exceed 50% of mean, all four methods are equal. The method of choice depends on the resources available, the differences to be detected, and what additional information, such as leaf weight or stalk weight, is also desired.

Table B3.1 Minimum number of plants required to detect true differences among treatments using $\alpha = 0.05$ and 0.01 test of significance and 90% probability of success ($\beta = 0.1$).

		Test of significance					
		$\alpha = 0.05$			$\alpha = 0.01$		
		True difference %					
Method	CV	10	20	50	10	20	50
	%	------- no. of plants ---------					
I	9.4	21	7	2	29	10	3
II	14.7	44	13	4	63	18	5
III	10.2	23	7	2	32	10	3
IV	11.6	31	9	3	43	13	4

Table B3.2 Relative costs for measuring leaf area of one corn plant with 12 to 14 leaves.

Method	Activity	Time man-min/plant
I.	Measure area of all leaves	8
II.	Measure area and weight of subsample of leaves	9
.	Measure weight of large sample of leaves	4
III.	Measure length and width of all leaves	6
IV.	Measure length and width of all leaves in one replicate	6
	Measure length and width of largest leaf in other replicates	1

$Cost_1$ = n (8 min/plant).
$Cost_2$ = (9 min/plant + (n - 1)(4 min/plant).
$Cost_3$ = n (6 min/plant).
$Cost_4$ = (10/r)(6 min/plant) + (n)(1 min/plant), where r is replicate (e.g., assumed that r = 4) and n is number of plants on which only largest leaf is measured.

Table B3.3 Total relative costs for measuring leaf area of corn plants.

		Test of significance					
		$\alpha = 0.05$			$\alpha = 0.01$		
		True difference %					
Method	CV	10	20	50	10	20	50
	%	-------- man-min ----------					
I	9.4	168	56	16	232	80	24
II	14.7	181	57	21	257	77	25
III	10.2	138	42	12	192	60	18
IV	11.6	46	24	18	58	28	19

B.4. Changes in Spectral Properties of Detached Birch Leaves.
      C. S. T. Daughtry and L. L. Biehl

A leaf begins to senesce as soon as it is removed from the plant and changes in metabolic processes and spectral properties are inevitable. The objectives of this study were to (1) determine the rate of changes in spectral properties of detached leaves and (2) evaluate the effectiveness of low temperature and cytokinin for delaying changes in spectral properties.

Leaves from red birch (Betula nigra L.) were immersed for 5 min in water or 0.001 M benzylaminopurine (BAP) and stored in plastic bags in the dark at either 5 or 25°C. Total directional-hemispherical reflectance and transmittance of the adaxial surface of leaves were measured over the 400-1100 nm wavelength region (Fig. B4.1) with a spectroradiometer and integrating sphere (LI-COR LI-1800).

Spectral properties changed less than 5% of initial values during the first week when leaves were stored at 5°C (Fig. B4.2). Storage at 25°C promoted rapid senescence and large changes in spectral properties. BAP delayed, but did not stop, senescence at 25°C (Fig. B4.3). Low temperature was more effective than BAP in delaying senescence. It appears possible to store leaves at low temperatures in plastic bags in the dark for several days without significantly altering the spectral properties in the 400-1100 nm wavelength region.

Figure B4.1 Reflectance, and transmittance of birch leaves treated with water and stored at 25°C, as a function of wavelength and time after excision. Data are means of three leaves. Absorptance is calculated as 100 minus the sum of reflectance and transmittance.
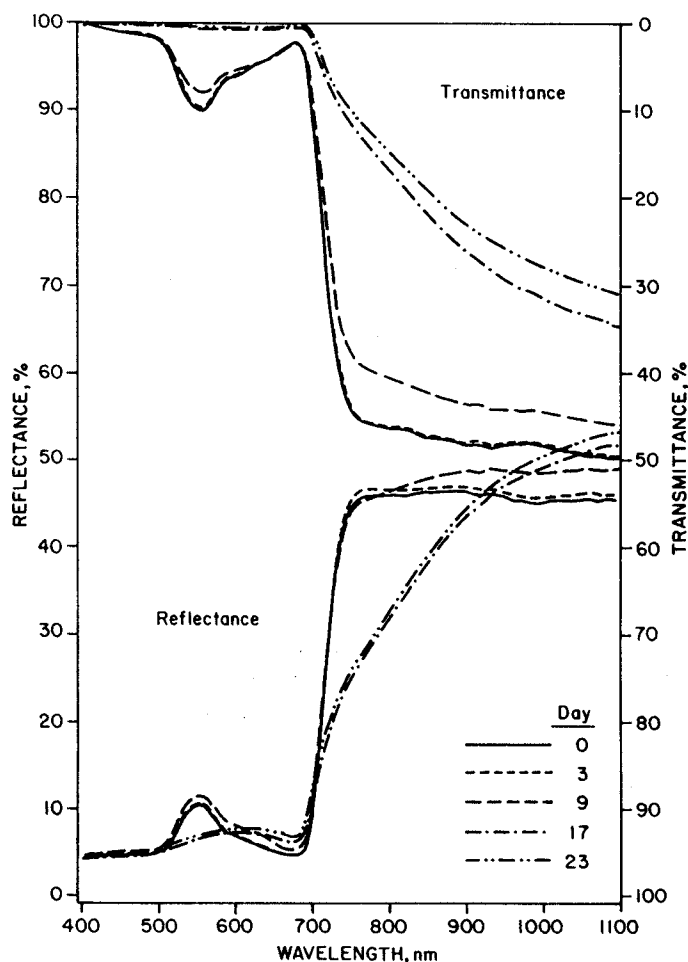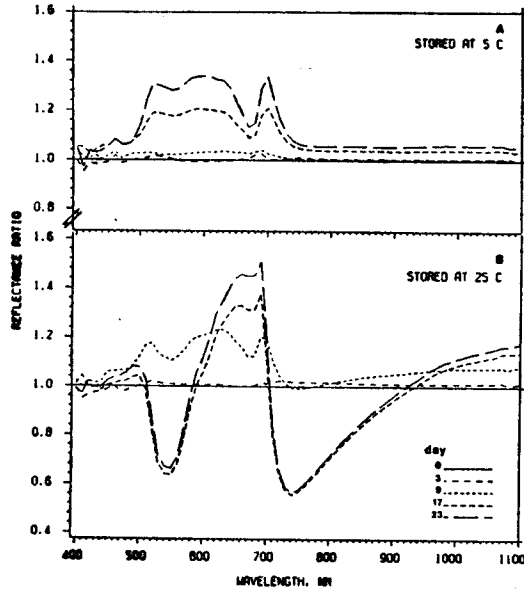
Figure B4.2 Changes in reflectance of birch leaves treated with water as a function of wavelength and time after excision. Data are ratios of reflectance on day n divided by reflectance on day 0.
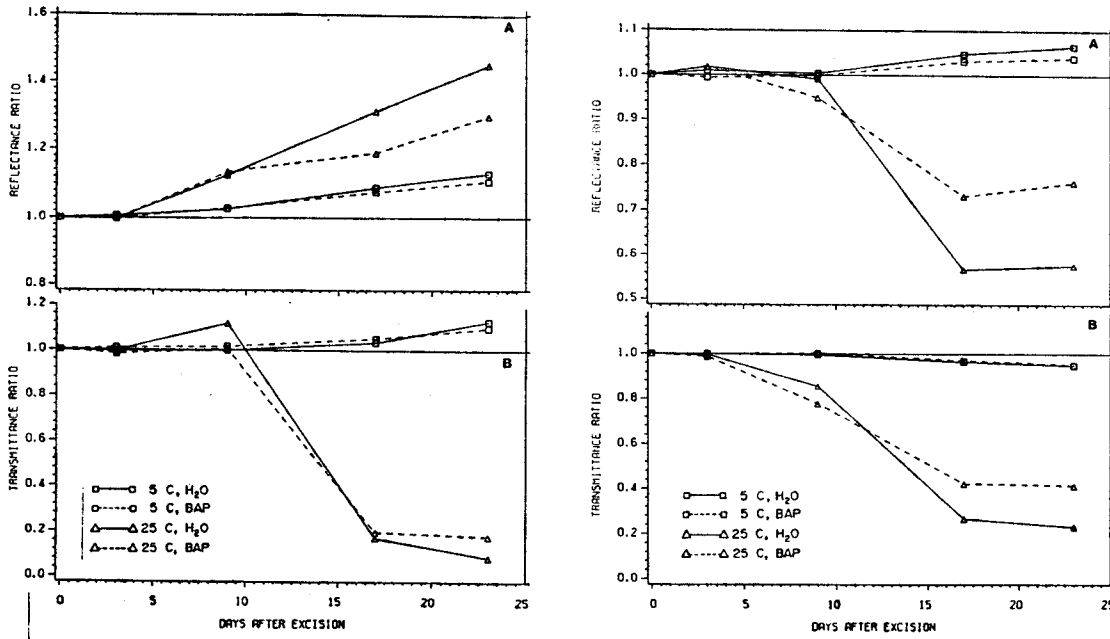
Figure B4.3 (left) Changes in reflectance and transmittance of birch leaves at 670 nm as a function of time after excision. Data are ratios of reflectance on day n divided by reflectance on day 0.

Figure B4.4 (right) Changes in reflectance and transmittance of birch leaves at 750 nm as a function of time after excision.

B.5. Two-dimensional leaf orientation distributions.*
Donald E. Strebel, Narendra S. Goel, and K. Jon Ranson

Combined inclination/azimuth leaf angle distributions are important for accurate models of vegetation canopy reflectance. It is shown that appropriate mathematical representations can be constructed from beta distributions under most circumstances. This is illustrated by analyzing observational data on soybean leaves (Fig. B5.1) and balsam fir needles (Fig. B5.2).

There are some problems when the data is imprecise and when correlations between inclination and azimuth angle are induced by heliotropism. Otherwise, the two-dimensional beta-type distribution appears to be a versatile tool for describing complete inclination/ azimuth leaf angle distributions
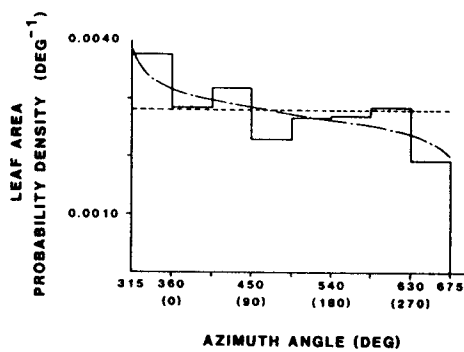
(a)
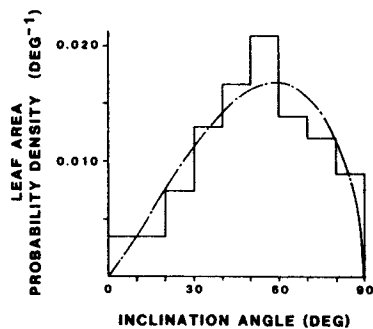
(b)
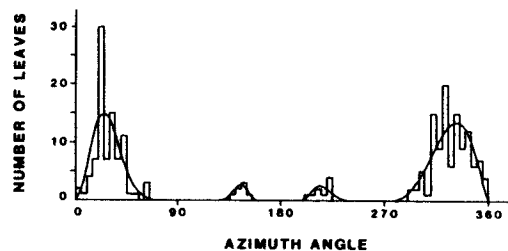
Figure B5.2. Balsam fir needle azimuth angle histogram and the fitted probability distribution comprised of four beta distributions.

Figure B5.1. Soybean leaf area distributions.(a) Azimuth angle. (b) Inclination angle.Measured values are shown as histograms.(_._) curve represents the fitted beta distribution. In (a) the dashed line is the corresponding uniform distribution.

B.6.   A New Technique to Measure the Spectral Properties
       of Conifer Needles.
       L. L. Biehl, C. S. T. Daughtry and K. J. Ranson.

As models have been developed which describe interactions of solar radiation with plant canopies, the need for accurate and reliable measurements of the spectral properties of leaves has increased. Instruments capable of measuring the optical properties of leaves and other canopy elements typically have integrating spheres with sample ports at least 1.0 cm in diameter. For example the sample port of the integrating sphere of the LICOR LI-1800 spectroradiometer is 1.45 cm with an illumination beam diameter of 1.14 cm. These dimensions are well suited for leaves of many species which are larger than 1.5 cm. However for the narrow leaves of many grasses and the needles of conifers, the sample port and illumination beam diameters are too large.

Simply reducing the sample port diameter will not suffice unless the beam illuminating the sample is also reduced. Restricting both sample port size and illumination beam width to the dimensions of a black spruce needle (10-20 mm long and 1-2 mm wide), for example, may significantly degrade the spectral sensitivity of the spectroradiometer especially for wavelengths where absorption is high and reflectance and transmittance are low.

Thus alternative strategies are needed to measure the spectral properties of conifer needles. One alternative approach frequently used is to make a "solid" mat of needles by laying needles side by side. This mat of needles is then placed over the sample port and its spectral properties are measured. This techniques has several problems. First it is difficult to arrange conifer needles in a single layer with no gaps between needles. A few gaps may be acceptable for reflectance measurements but not for transmittance measurements. Even one small gap between the needles may allow much more radiation into the integrating sphere than the rest of the sample, especially in the region of the spectrum where transmittance is low. Making the mat of needles several layers thick only confounds the measurements due to multiple scattering in the additional layers.

A second alternative approach for conifer needles is to consider the twig and its needles as the basic element of the canopy and to measure the spectral properties of the entire ensemble. However to our knowledge, no spectroradiometer and integrating sphere in production has the depth of field and size required to accommodate such an ensemble of needles. This is an area of current research by Darrell Williams at Goddard Space Flight Center.

Our objectives were (1) to determine a theoretical basis for measuring the optical properties of conifer needles and (2) to test the algorithm and procedure using simulated and real needles. We present three cases with equations for calculating reflectance and transmittance of leaves. Although the equations were developed for the LICOR LI-1800 spectroradiometer and integrating sphere, the concepts are applicable to other spectrophotometers with integrating spheres.

Case 1.

In the first case we review the standard calculation of reflectance and transmittance when the leaf covers the entire sample

$$\text{Reflectance} = P_S = \frac{F_R - F_N}{F_W - F_N} \cdot \frac{P_R}{G_2} \qquad [1]$$

$$\text{Transmittance} = T_S = \frac{F_T}{F_W - F_N} \cdot \frac{P_R}{G_2} \qquad [2]$$

where:

F_R = flux measured in reflectance mode
F_N = flux measured in reflectance mode with no sample, i.e., stray light
F_W = flux measured in reference mode
F_T = flux measured in transmittance mode
P_R = reflectance of calibration reference surface
G_2 = function of sphere reflectance and geometry and sample reflectance. Values for the LI-1800 range between 1.000 and 1.008. Assumed in calculations to be 1.000.

Case 2.

The second case deals with conifer needles that are longer than the diameter of the sample port of the integrating sphere. For example needles of red pines may exceed 10 cm in length. The needles may be laid side by side approximately a needle width apart and the ends of the needles may be taped together for easier handling.

$$P_S = \frac{F_R - F_N}{F_W - F_N} \cdot \frac{P_R}{1 - F_B} \cdot \frac{1}{G_1} \qquad [3]$$

$$T_S = \left[\frac{F_T}{F_W - F_N} \cdot P_R - P_W \cdot F_B \cdot G_3 \right] \frac{1}{1 - F_B} \cdot \frac{1}{G_1} \qquad [4]$$

$$F_B = \left[\frac{F_T}{F_W - F_N} \cdot P_R - B_1 \cdot T_S \right] \cdot \frac{1}{P_W \cdot C_1 - B_1 \cdot T_S} \qquad [5]$$

Where:

P_W = reflectance of the sphere wall
F_B = portion of the beam area that does not strike the sample.
B_1, C_1, G_1, G_3 = functions of sphere reflectance and geometry, sample reflectance and the area of the beam that does not strike the sample. Values for the LI-1800 range between 1.000 and 1.008 Assumed in calculations to be 1.000.

The key concept is that is area of the illumination beam that does not strike the the sample (F_B) can be calculated and used to correct the reflected and transmitted fluxes. The area, F_B, is measured as the ratio of flux at 680 nm transmitted through the blackened sample (i.e., no radiation transmitted through the needles themselves) to the flux at 680 nm transmitted though the normal (unblackened) sample. This wavelength was chosen because green leaves typically have minimum transmittance at 680 nm.

Case 3.

The third case extends the concept presented in Case 2 and deals with conifer needles that are shorter than the diameter of the sample port of the integrating sphere. For example needles of black spruce typically are only 1-2 cm long. In this case the needles were removed from the twig and carefully arranged on a specularly transmitting background., i.e., Scotch brand Magic Transparent tape no. 810.

$$P_S = [\frac{F_R - F_N}{F_W - F_N} \cdot P_R \cdot \frac{1}{B_1} - F_{BB} \cdot P_B] \cdot \frac{1}{1 - F_B} - T_S^2 \cdot P_B \qquad [6]$$

$$T_S = [\frac{F_T}{F_W - F_N} \cdot \frac{P_R}{T_B} - P_W \cdot F_{BB} \cdot C_1] \cdot \frac{1}{1 - F_B} \cdot \frac{1}{B_1} \qquad [7]$$

$$F_{BB} = [\frac{F_T}{F_W - F_N} \frac{P_R}{T_B} - B_1 T_S] \cdot \frac{1}{(P_W \cdot C_1) - (B_1 \cdot T_S)} \qquad [8]$$

Where:

P_B = reflectance of the background (i.e., tape)
T_B = transmittance of the background
F_{BB} = portion of beam area that does not strike the sample that is mounted on a specularly transmitting background.

<u>Recommended procedure</u> for measuring the optical properties of black spruce needles.

1. Measure reflectance and transmittance of tape with sticky side toward the illumination source.

2. Detach needles from its twig and place on the tape with approximately one needle width apart. When placed closer than one needle width reflectance increased apparently due to multiple reflections from adjacent needles.

3. Select a sample holder that is approximately 0.5 needle thick and place in the sample port of the integrating sphere with the needles toward the sphere.

4. Measure spectral response in reflectance mode and in the reference mode (Figure B6.1)

5. Rotate sample holder so that needles are away from the sphere and measure spectral response in transmittance mode and in reference mode. (Figure B6.1).

6. Blacken the needles with opaque paint and remeasure spectral response in transmittance mode.

7. Compute F_{BB} at 680 nm (or F_B for Case 2) using the transmittance of the blackened needles. This assumes that the transmittance of the blackened needles at 680 nm is 0.0.

8. Compute transmittance and reflectance of the normal needles.

As a test of this algorithm and procedure, reflectance and transmittance of squares of green Nextal suede coated paper that completely covered the sample port of the integrating sphere were measured (Case 1). The squares were cut into narrow strips approximately 1-2 mm wide and the spectral properties remeasured without (Case 2) and with (Case 3) the tape background. The results for Cases 2 and 3 which simulated conifer needles were within 4% of the values for Case 1 which simulated a broad leaf. Some of the differences observed were due to the cut edges of the Nextal paper which were gray, not green. When these procedures were tested with five sets of 3, 7, and 11 black spruce needles from the same branch, the coefficients of variation (CV) were less than 8%. When either 7 or 11 needles per set were measured the CV was less than 5%. Thus the procedure appears to produce repeatable and reliable results.

Figure B6.1. The integrating sphere of the LI-1800 configured in (A) the reference mode, (B) the reflectance mode and (C) the transmittance mode. Measurements are taken by placing the illuminator in the reference port and taking a reference scan. The reference material and the material coating the walls of the integrating sphere is barium sulphate ($BaSO_4$). After a reference scan, the illuminator is moved to the reflectance or transmittance port in order for the source to shine on or through the sample, respectively.
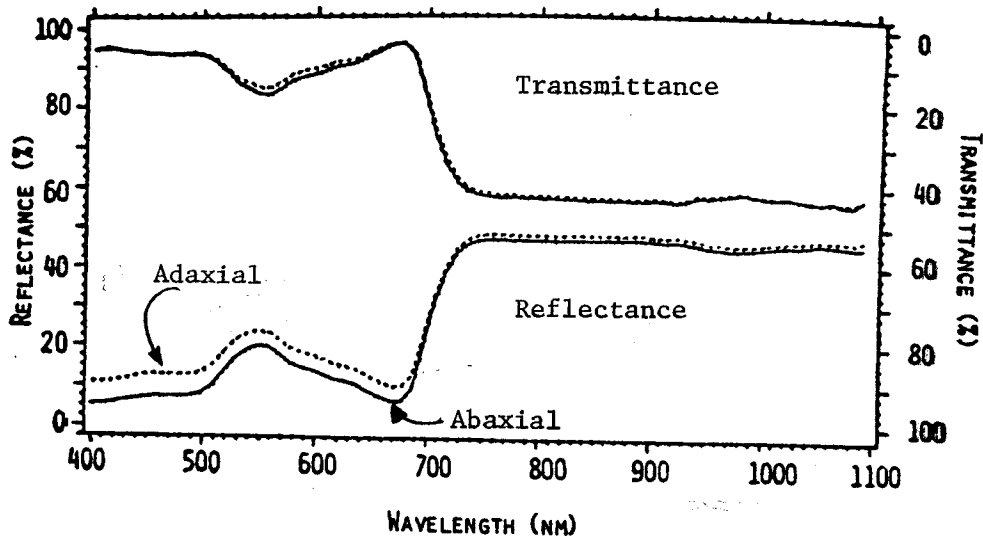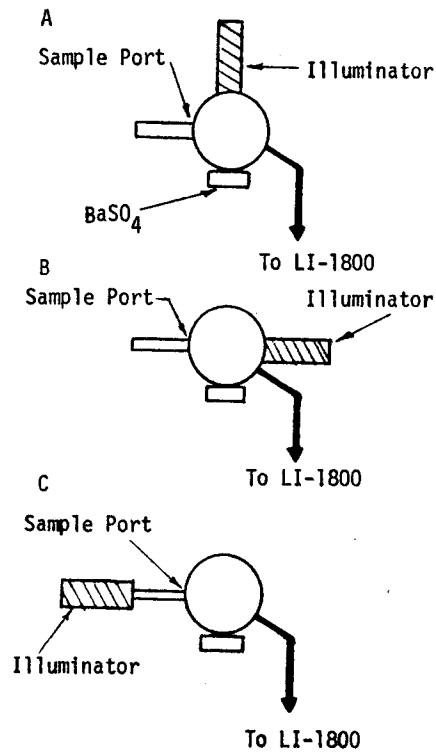

Figure B6.2. Reflectance and transmittance of black spruce needles (Case 3).

B7. Multispectral Properties of Aspen Leaves.
     C. S. T. Daughtry, L. L. Biehl, and K. D. Woods.

Several models describing the interactions of visible and infrared radiation with plant canopies have been proposed and evaluated. Each of these models requires accurate measurements of the multispectral properties of the components of plant canopies (i.e., leaves, stems, inflorescences, and soil). For example Goel and coworkers demonstrated that a small change in hemispherical reflectance and transmittance of leaves may produce large changes in the values of leaf area index predicted by inverting the Suits' model of canopy reflectance. Many factors affect the spectral properties of leaves including chlorophyll content, water content, leaf age, internal leaf structure, nutrient deficiency or excess, light intensity, diseases and insects.

To describe the natural variability of spectral properties in plant canopies requires that one select representative samples and avoid introducing extraneous variation due to the measurement process. Our objectives were to (1) describe the multispectral properties of quaking aspen (Populus tremuloides Michx.), (2) quantify some sources of variation in multispectral properties of aspen leaves, and (3) estimate the number of samples required to detect desired differences in spectral properties.

Instruments capable of accurately measuring the multispectral properties of plant components frequently are not well suited for in situ measurements either in remote areas or at the top of tall trees. When leaves are detached from trees, they begin to senesce and changes in metabolic processes and spectral properties are inevitable. However in a previous section (II.B.4), we demostrated that the rate of senescence can be slowed significantly by keeping the leaves cool in sealed plastic bags. The spectral properties (400-1100 nm) of green leaves changed by less than 5% of initial values during the first week after excision when stored at 5° C. Thus it is possible to store leaves at low temperatures in plastic bags for several days without significantly altering the multispectral properties of leaves.

During August 1983 five quaking aspen trees were selected at random from test sites with different age groups of trees within the Superior National Forest near Ely, MN. The crown of each tree was stratified in to thirds and 10 green leaves were selected at random from each stratum. A total of 30 leaves per tree was acquired. The leaves were placed in polyethylene bags, packed in insulated containers with ice, and mailed to Purdue University. At Purdue the leaves were unpacked and stored at 5° C until their spectral properties were measured. Total elapsed time from excision to measurement was less than 7 days.

Total (diffuse + specular) directional-hemispherical reflectance and transmittance of both adaxial and abaxial surfaces of the aspen leaves were measured over the 400 to 1100 nm wavelength region with a spectroradiometer and integrating sphere (LICOR LI-1800). The incidence angle of illumination was 5 degrees from normal. An area between the major veins of each leaf was identified and measured each

between the major veins of each leaf was identified and measured each time to minimize within-leaf variation in spectral properties. All data were corrected for reflectance of the BaSO$_4$ reference surface in the integrating sphere and expressed in directional-hemispherical reflectance and transmittance factor units. Absorptance was calculated as 1.0 minus the sum of reflectance and transmittance.

The mean spectral properties of aspen leaves are shown in Figure B7.1. The variation in reflectance and transmittance among healthy leaves is relatively small. Both surfaces of aspen leaves are glabrous (smooth) however the abaxial (lower) surface is more reflective than the adaxial (upper) surface in the visible (400-700 nm). In the near infrared (700 -1100 nm) region there are no significant differences between the surfaces of aspen leaves. Because the petioles of quaking aspen are laterally flattened, the leaves easily move from side to side and often flip over in a gentle or moderate breeze. Thus aspen trees present ever changing proportions of both leaf surfaces when view from above. The effect of position of leaves on the trees on the spectral properties varied depending on stand density, but generally the differences were small (fig. B7.2).

The variation in reflectance of aspen bark (Fig. B7.3) was greater than the variation in reflectance among the leaves (Fig. B7.1). The bark of young aspen is smooth and is greenish white to cream-colored. Old aspen will have bark that is furrowed and dark brown or gray-colored on the bole and major branches, however the small branches will have bark similar to young aspen.

In practice a researcher wants to know how many observations must be acquired to be reasonably confident of detecting specific differences among various species or classes of trees, He must decide how small a difference among classes must be detected, i.e., how large an error in spectral properties can be tolerated. This demands careful thinking about the use to be made of the estimates of spectral properties and about the consequences (costs) of a sizeable error. Initially the acceptable error limits may be quite arbitary or they may be derived from a sensitivity analysis of a particular canopy reflectance model. In either case the error limits represent a goal which can be refined as experience is gained.

We chose four degrees of precision among treatments, i.e., 5, 10 , 20, and 50% of the mean reflectance. We also specified that we wanted to be 90% confident of detecting significant differences at the alpha = 0.10 level. Table B7.1 shows the coefficients of variation and the minimum number of measurements required to detect true differences in reflectances at selected wavelengths among healthy aspen leaves. The standard deviations for the reflectance measurements were approximately 1.5 across all wavelengths. However the CV for visible wavelengths are 3 to 5 times larger than in the near infrared because the means of reflectance in the visible are much lower than in the near infrared. Thus to achieve the desired degree of precision in the visible wavelength region requires many observations. For example to detect difference of less than 20% of the mean reflectance in the visible region requires at least 22 to 35 observations.

Table B7.1. Minimum number of observations required to detect true differences among reflectances of leaves using α = 0.10 tests of significance and a 90% probability of success (β = 0.1).

Wavelength	mean	s.d.	CV	True Differences, %			
				5	10	20	50
nm	%	%	%	-- no. of observations -			
450	7.8	0.91	11.6	>100	22	7	2
500	8.9	1.10	12.4	>100	28	8	2
550	16.2	1.81	11.2	85	22	7	2
600	11.9	1.59	13.4	>100	32	9	2
650	9.0	1.25	13.9	>100	35	10	2
700	15.5	1.66	10.7	77	20	6	2
750	46.4	1.36	2.9	7	2	2	2
800	47.0	1.45	3.1	8	3	2	1
900	47.1	1.50	3.2	8	3	2	1
1000	45.7	1.52	3.3	9	3	2	1
1100	45.8	1.53	3.3	9	3	2	1

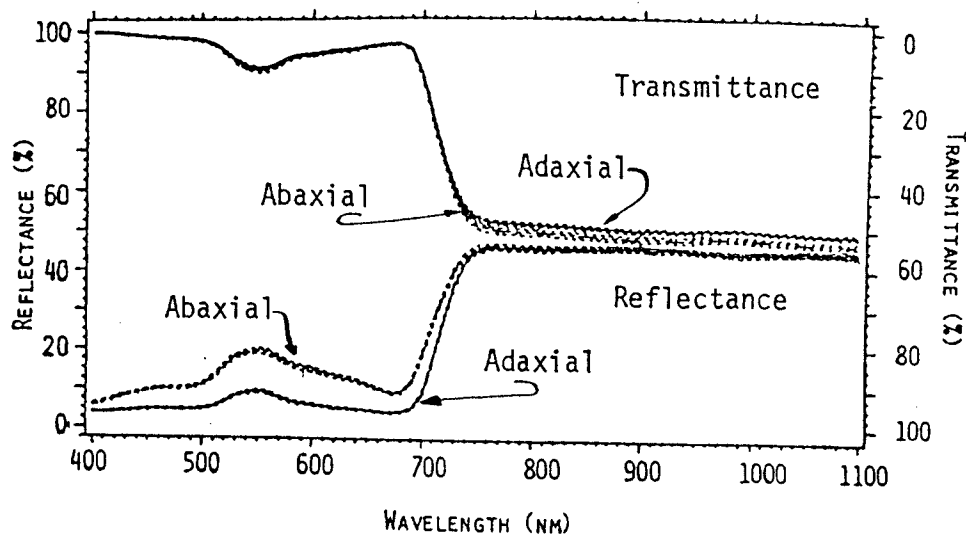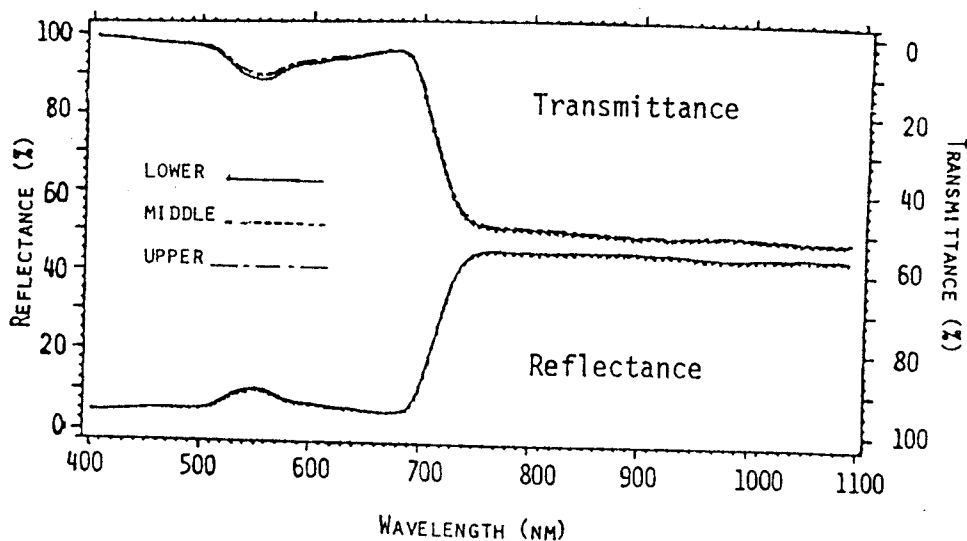Figure B7.1. Mean reflectance and transmittance of abaxial and adaxial surfaces of aspen leaves.

Figure B7.2. Mean reflectance and transittance of the adaxial surfaces of 10 aspen leaves from three strata (upper, middle, and lower thirds of crown) of a tree from a medium density site in Superior National Forest in 1983.
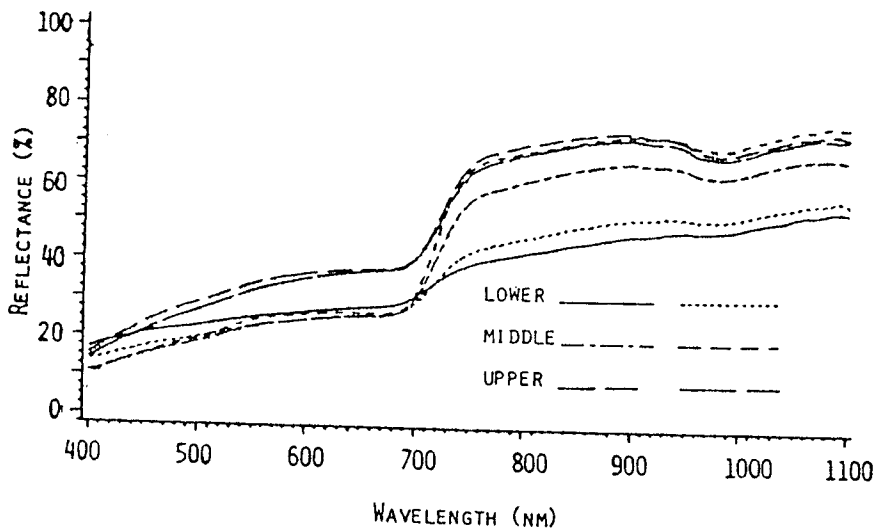

Figure B7.3. Mean relectance of samples of bark from three strata of aspen trees in 1983.

C. Spectral Measurements of Intercepted Radiation.

C.1.   Spectral Estimates of Solar Radiation Intercepted
        by Corn Canopies.
        C. S. T. Daughtry, K. P. Gallo, and M. E. Bauer

As the need for timely information on worldwide crop production
intensifies the role of remote sensing is becoming more prominent. If
agronomic variables related to yield could be reliably estimated from
multispectral satellite data, then crop growth and yield models could be
implemented for large ares. The objective of this experiment was to
develop methods for combining spectral and meteorological data in crop
yield models that are capable of providing accurate estimates of crop
condition and yields.

Initial tests of this concept using data acquired in field
experiments at the Purdue Agronomy Farm, West Lafayette, Ind., are
presented. Reflectance factor data were acquired with a Landsat band
radiometer throughout two growing seasons for corn (Zea mays L.)
canopies differing in planting dates, populations, and soil types (Typic
Argiaquoll and Udollic Ochraqualf). Agronomic data collected to
coincide with the spectral data included leaf area index (LAI)),
biomass, development stage, and final grain yields.

The spectral variable, greenness, was associated with 76% of the
variation in LAI over all treatments. Single observations of LAI or
greenness were found to have limited value in predicting corn yields
(Fig.C1.1). The proportions of solar radiation intercepted (SRI) by
these canopies were estimated using either measured LAI or greenness.
Both estimates, when accumulated over the growing season, accounted for
approximately 65% of the variation in yields. The Energy Crop Growth
(ECG) variable was used to evaluate the daily effects of solar
radiation, temperature, and moisture stress on corn yields.
Coefficients of determination for grain yields were 0.67 for the ECG
model using measured LAI to estimate SRI, and 0.68 for the ECG model
using greenness to estimate SRI (Fig. C1.2).

We conclude that this concept of estimating intercepted solar
radiation using spectral data represents a viable approach for merging
spectral and meteorological data in crop yield models. The concept
appears to be extendable to large areas by using Landsat MSS data along
with daily meteorological data and could form the basis for a future
crop production forecasting system.

Figure C1.1. Corn grain yields as function of maximum greenness. RMSE is 2.6 tons/ha. The symbols are the relative planting dates for the two years with "0" representing the first planting date in 1979 and "9" the last planting date in 1980.
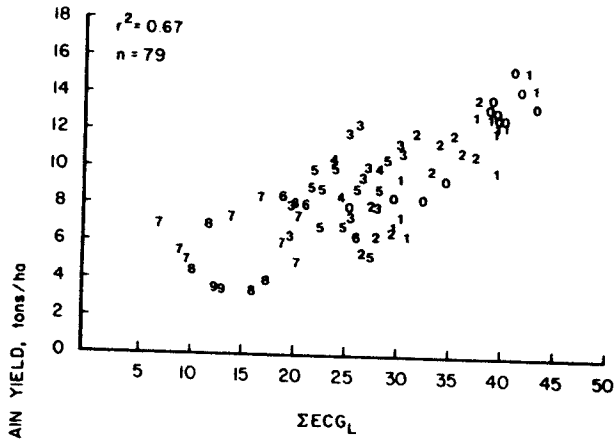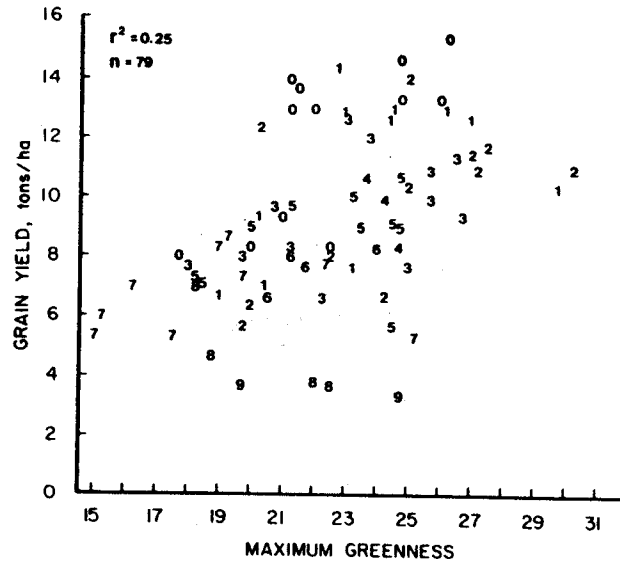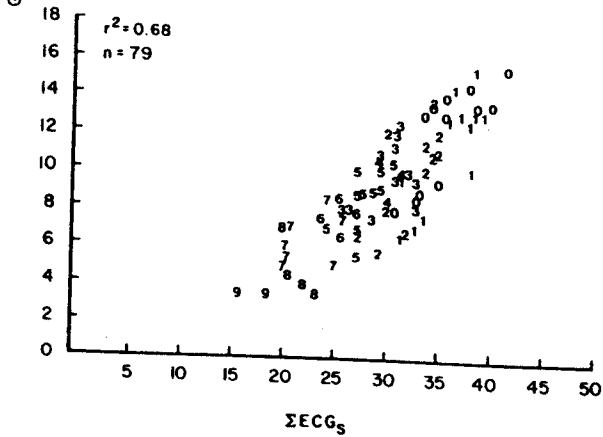

Figure C1.2. Corn grain yields as a function of the accumulated ECG variable. The ECG_L is calculated using SRI_L and ECG_S with SRI_S. RMSE is 1.7 tons/ha for both ECG models.

C.2. Spectral Estimation of Absorbed Photosynthetically Active
      Radiation in Corn Canopies.
      K. P. Gallo, C. S. T. Daughtry, and M. E. Bauer

Most models of crop growth and yield require an estimate of canopy
leaf area index (LAI) or absorption of radiation; however, direct
measurement of LAI or light absorption can be tedious and time-
consuming. The object 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 north-south rows at densities of 50,000 and 100,000 plants ha.$^{-1}$

Two distinct relationships between absorbed PAR and LAI were
observed (Fig. C2.1). Absorbed PAR increased as a function of green LAI
from planting to a maximum at anthesis or silking and then decreased at
a different rate to maturity. Beer's law described the relationship
between absorbed PAR and LAI from planting to maturity. The different
relationships before and after silking are due to the absorption of PAR
by nongreen parts of the canopy after silking.

Reflectance factor data were acquired with a radiometer with
spectral bands similar to the Landsat MSS. Three spectral vegetation
indices (ratio of near infrared to red reflectance, normalized
difference, and greenness) were associated with more than 95% of the
variability in absorbed PAR from planting to silking. The relationships
developed between absorbed PAR and the three indices were tested with
reflectance factor data acquired from corn canopies planted in 1979-1982
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^{-1}), three soil types
(Typic Argiaquoll, Udollic Ochraqualf, and Aeric Ochraqualf), and
several planting dates in each year.

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 (Table C2.1). Seasonal cumulations of daily
absorbed PAR, estimated indirectly from the multispectral reflectance of
the canopies, were associated with up to 73% of the variation in final
grain yields (Fig. C2.2). Absorbed PAR, cumulated through the growing
season, is a better indicator of yield than cumulated leaf area index.
These results suggest that absorbed PAR may be estimated from canopy
spectral reflectance for large areas where direct measurement of LAI or
absorbed PAR would prohibitive. Thus models of crop yields which
require estimates of absorbed PAR may be implemented and evaluated.

Table C2.1. 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

Figure C2.1 (right) Relation between absorbed PAR and leaf area index for growth (planting to silking, squares) and senescent (silking to maturity, asterisks) periods of corn development. The fitted regression is for the period from planting to silking.
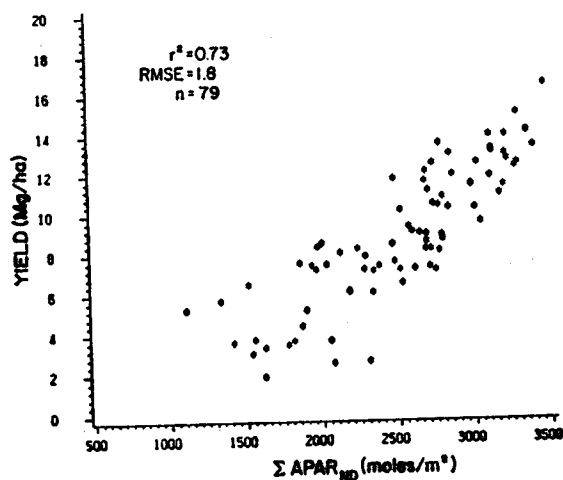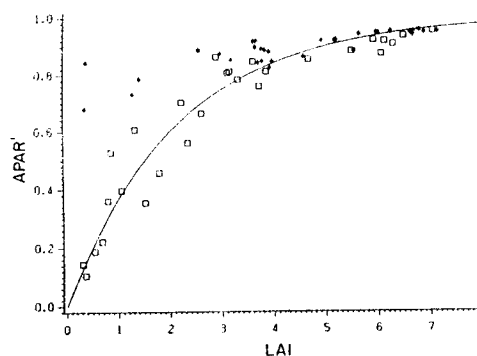Y = 1 - exp(-0.46 LAI).

Figure C2.2 (left) Grain yields of corn from test years displayed as a function of absorbed photosynthetic photon flux density (APAR). r^2 = 0.73; RMSE = 1.8; n = 79.

C.3. Light Interactions with Soybean Canopies
       C. C. Brooks and C. S. T. Daughtry

Photosynthetically active radiation (PAR) is the source of energy for photosynthesis and is defined as the 400-700 nm wavelength portion of the solar radiation spectrum. PAR is available as an energy source for photosynthesis only when it interacts with green leaves or other chlorophyll-containing plant structures. In a healthy plant adequately supplied with water, the production of dry matter is proportional to the quantity of PAR intercepted by the plant. Thus important components of plant growth and yield are the amount and duration of plant surfaces capable of photosynthesis. Current methods to measure the leaf aread index and or the quantity of PAR intercepted by plant communities are laborous at best and limit the use of intercepted radiation models to small research plots. If the proportion of PAR intercepted by plants could be reliably estimated with multispectral reflectance data, then the capability to estimate crop production over large regions could be improved significantly.

A study was conducted at the Purdue Agronomy Farm near West Lafayette, IN to (1) examine the effects of management practices on the efficiency of converting intercepted PAR into dry phytomass and yield, (2) develop a method of estimating LAI from measurements of PAR transmitted through plant canopies, and (3) develop methods of estimating leaf area index (LAI) and intercepted PAR from multispectral reflectance data. Soybeans (Glycine max (L.) Merr.) were planted on several dates and row widths in each of three years. The proportion of incident PAR transmitted (TPAR) through the plant canopy to the soil surface was measured periodically during each growing season. Intercepted PAR (IPAR) was calculated as 1.0 minus TPAR.

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 cummulated from planting to physiological maturity was highly correlated with total dry phytomass and grain yield (r^2 = 0.86). Mean efficiency of conversion of IPAR into total above ground dry phytomass was greatest for soybeans in narrowest row spacings (18 cm). Mean efficiency during the reproductive stage was nearly double that during the vegetative stage (Table C3.1). 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.

The relative intensity of radiation throughout a uniform canopy may be described by the following modification of the Beer-Lambert law:

$$I/I_o = e^{-k \; LAI}$$

where I/I_o is the proportion of incident radiant energy received at the bottom of an increment of leaf area index (LAI) and k is the extinction coefficient. The term I/I_o is equivalent to transmitted PAR (TPAR) as defined above. Reported values of k range from 0.2 to 2.0 depending on many factors including species, cultivar, management practices, sun

angles, and foliage movement. Values of k were determined for soybeans throughout the growing season at various sun angles and were used to predict LAI of soybeans in an independent test. For the test data models which limited solar zenith angles to 57.5 $\pm$ 10 degrees consistently had the lowest bias and the highest accuracy (mean error of less than 0.5 LAI).

The relationships between the spectral variables (greenness, normalized difference, and ratio of near infrared/red) and the agronomic variables (LAI and IPAR) were developed on data from 1982 and tested on data from 1983 and 1984. Although both LAI and IPAR could be estimated with the spectral variables, the errors increased as LAI exceeded 5.0 and IPAR exceeded 90%. Thus remotely sensed data may provide important information for models of crop growth and evapotranspiration.

Table C3.1 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.

D. Spectral Measurements of Phytomass, Leaf Area Index,
    and Stage of Development

D.1. Effects of Nitrogen Fertilization on Growth and Reflectance
       Characteristics of Winter Wheat
       L. D. Hinzman, M. E. Bauer, and C. S. T. Daughtry

       A valuable input to crop growth and yield models would be
estimates of current crop condition. If multispectral reflectance
indicates crop condition, then remote sensing may provide an additional
tool for crop assessment.

       Field experiments were conducted on a typic Argiaquoll at the
Purdue Agronomy Farm, West Lafayette, IN to (1) determine the effects of
nitrogen fertilization on the spectral reflectance and agronomic
characteristics of winter wheat (Triticum aestivum L) and (2) relate key
agronomic and spectral characteristics of wheat canopies. The
fertilization treatments consisted of 0, 60, and 120 kg N/ha, applied as
urea in the spring. Spectral reflectance was measured 11 times during
the 1979 growing season and 10 times during the 1980 growing season with
a spectroradiometer (Exotech 20C) in the 400-2400 nm wavelength region.
Agronomic data included total leaf N concentration, leaf chlorophyll
concentration, stage of development, leaf area index, plant moisture,
and fresh and dry phytomass.

       Relationships between spectral and agronomic variables were
developed using data from 1979 and tested with data from 1980. Nitrogen
fertilization of wheat reduced visible, increased near infrared, and
deceased middle infrared reflectance (Fig D1.1). These changes were
related to lower levels of chlorophyll and reduced leaf area in the
nonfertilized plots. Green LAI, an important descriptor of wheat
canopies, could be reliably estimated with multispectral data (Fig.
D1.2).

       The concentration of chlorophyll in the leaves is sensitive to
physiological stresses. Nitrogen fertilization increased chlorophyll
concentration in the leaves and produced more leaves per unit of soil.
As shown in previous studies red reflectance of a single leaf was highly
correlated to chlorophyll concentration. However for canopies IR/red
reflectance ratio of a canopy was highly correlated to the chlorophyll
density (Fig. D1.3) and leaf total N density (Fig. D1.4). Chlorophyll
density is defined as the product of leaf chlorophyll concentration and
green LAI. The leaf total nitrogen density was the product of total
nitrogen concentration of green leaves and dry phytomass of green
leaves.

       This study demonstrated that nitrogen-stressed wheat could be
distinguished from healthy wheat spectrally and, therefore, that
multispectral imagery may be useful for monitoring crop condition.
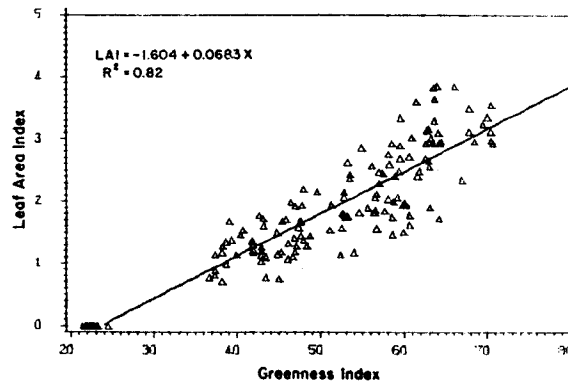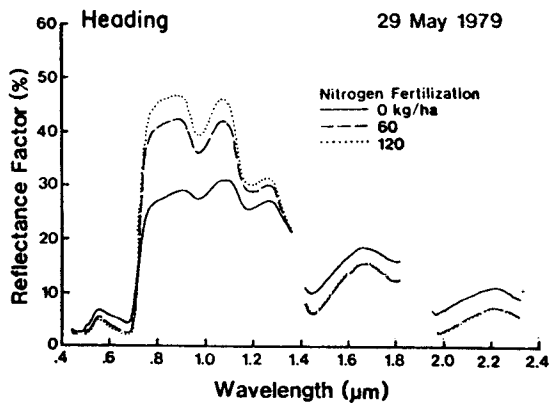
Figure D1.1 (left). Spectral reflectance of winter wheat at heading stage of development in 1979.

Figure D1.2 (right). Green leaf area index of winter wheat in 1979 plotted as a function of greenness index.
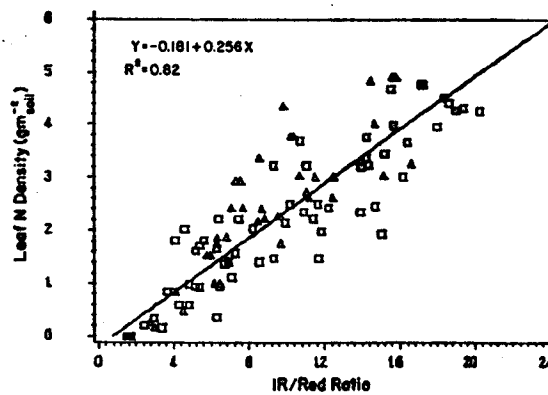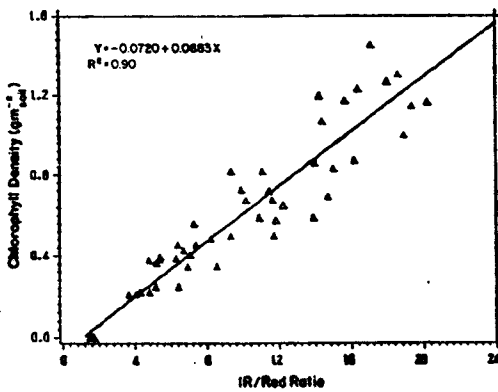
Figure D1.3 (left). Chlorophyll density of upper green leaves of wheat in 1979 plotted as a function of IR/red ratio.

Figure D1.4 (right). Leaf total N density of all green leaves of wheat in 1979 (squares) and 1980 (triangles) plotted as a function of IR/red ratio.

D.2. Effects of cultural practices on the spectral response of maize.
L. M. Nash, C. S. T. Daughtry and L. E. Schweitzer

Maize canopy growth and development are influenced by cultural and environmental factors. Understanding the effects of these factors on remotely sensed data is necessary for crop identification, condition assessment and yield estimation.

An experiment was conducted near West Lafayette, Indiana in 1979 to (1) determine the influence of management practices and soil color on spectral response and (2) predict canopy characteristics of leaf area index (LAI), percent soil cover, and phytomass from measurements of multispectral reflectance. Treatments imposed on one maize hybrid included three planting dates, three plant populations and two colors of soil background. Reflectance and agronomic data were collected on 22 dates throughout the growing season with spectral measurements in four wavelength bands (0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1 μm).

Linear and quadratic equations better described maize canopy traits as a function of reflectance for the period from planting to silking than from planting to harvest (Table D2.1). Percent soil cover and LAI were more accurately predicted than phytomass. The greenness transformation and the near infrared/red reflectance ratio (NIR/red) described these canopy characteristics better than single band reflectance measurements. These same transformations also appeared to be insensitive to the two colors of soil backgrounds in this study.

Early in the season planting date was the primary factor influencing both canopy development and spectral reflectance (Table D2.2). This trend continued into mid-season, when plant population began to account for increasing amounts of the variability. Late in the season, planting date was again the dominant factor as the plants senesced.

Crop yields increased with earlier planting dates and higher populations. Soil background did not affect crop growth and development, but it was a significant factor affecting reflectance of single bands early in the season when percent soil cover was low.

The use of growing degree units (GDU) minimized differences in canopy reflectance and growth properties due to planting date. Maximum LAI and reflectance values occurred at 1000 to 1200 GDU which corresponded to the end of vegetative development and the beginning of grain development. This information should be useful in developing crop models using remotely sensed data.

Table D2.1. Coefficients of determination (R^2) for several agronomic variables as a quadratic functions of red (600-700 nm) and near infrared (800-1100 nm) reflectance factor, near infrared/red ratio and greenness.

Agronomic variable	Red	NIR	NIR/ Red	Green- ness	Range

- - - - - - - - - R^2 - - - - - -

Planting to Silking

	Red	NIR	NIR/Red	Greenness	Range
Soil Cover	0.91	0.93	0.97	0.97	0-100%
Leaf Area Index	0.72	0.83	0.87	0.86	0-7.0
Fresh Phytomass	0.75	0.74	0.88	0.80	0-11.7 kg/m^2
Dry Phytomass	0.67	0.65	0.80	0.69	0-2.3 kg/m^2

Planting to Harvest

	Red	NIR	NIR/Red	Greenness	Range
Soil Cover	0.58	0.87	0.75	0.89	0-100%
Leaf Area Index	0.65	0.71	0.78	0.78	0-7.0
Fresh Phytomass	0.46	0.55	0.52	0.58	0-11.7 kg/m^2
Dry Phytomass	0.11	0.20	0.14	0.22	0-3.2 kg/m^2

Table D2.2. Percent variation (R^2) in leaf area index, NIR/red ratio, greenness associated with soil color, planting date, and plant density of corn in 1979.

	Observation Date				
Factor	6/11	6/25	7/10	8/8	9/17

Leaf Area Index

	6/11	6/25	7/10	8/8	9/17
Soil Color	2	3	9	13	5
Planting Date	68	68	25	4	21
Plant Density	15	22	37	21	15

NIR/Red

	6/11	6/25	7/10	8/8	9/17
Soil Color	18	8	7	2	2
Planting Date	49	59	41	22	65
Plant Density	8	20	42	18	11

Greenness

	6/11	6/25	7/10	8/8	9/17
Soil Color	1	0	0	5	10
Planting Date	72	70	34	8	41
Plant Density	13	23	51	18	7

D.3. Estimating silking and maturity dates of corn for large areas.
      C. S. T. Daughtry, J. C. Cochran, and S. E. Hollinger

Crop development involves complex physiological and biochemical processes which are influenced by the crop's environment in ways that are still inadequately understood. Knowledge of when critical crop stages occur and how the environment affects them should provide useful information for crop management decisions and crop production models.

This research evaluated two sources of data for predicting dates of silking and physiological maturity of corn (Zea mays L.). Initial evaluations were conducted using data of an adapted corn hybrid grown on a Typic Agriaquoll at the Purdue University Agronomy Farm from 1979 to 1981. The second phase extended the analyses to large areas using data acquired by the Statistical Reporting Service of USDA for crop reporting districts (CRD) in Indiana and Iowa from 1969 to 1980. These data from SRS represented means of adapted genotypes of corn in each CRD.

Four thermal models were compared to calendar days for predicting dates of silking and physiological maturity. The first index growing degree unit, GDU, is the simplest thermal model and is defined as the daily mean air temperature minus a base temperature for growth of 10 $^\circ$C. Modified growing degree unit (MGDU) index is the same equation as GDU but with a threshold of 30 $^\circ$C imposed on maximum temperature and a threshold of 10 $^\circ$C is imposed on the minimum temperature. Heat stress (HS) index is the same equation as MGDU but with a decrease in thermal unit accumulations for maximum temperatures greater than 30 $^\circ$C. Function of temperature (FT) index is mean of the relative growth rates for the daily maximum and minimum air temperatures. Mixed models which used a combination of thermal units to predict silking and days after silking to predict physiological maturity were also evaluated.

At the Agronomy Farm the models were calibrated and tested on the same data. For each CRD the models were calibrated using 4 or 5 years of data and tested using 7 different years of data. The thermal models were significantly less biased and more accurate than calendar days for predicting dates of silking (Table D3.1). Differences among the thermal models were small. Significant improvements in both bias and accuracy were observed when the mixed models were used to predict dates of physiological maturity (Table D3.2). The results indicate that statistical data for CRD can be used to evaluate models developed at agricultural experiment stations.

Table D3.1. Mean error (e), mean absolute errors (|e|), and standard deviation of absolute errors (SD) in days for predicted minus actual dates of silking in test years. Data are means of nine CRD, three planting dates per year, and 7 years for both Indiana and Iowa (n = 189).

		Thermal Models				Calendar
Location	Statistic	GDU	MGDU	HS	FT	Days
Indiana	e	0.5 a[+]	0.0 b	0.0 b	-0.8 c	-4.1 d
	|e|	2.8 b	2.4 c	2.3 c	2.4 c	5.9 a
	SD	2.3	2.1	2.0	2.0	4.3
Iowa	e	0.7 a	0.3 b	0.7 a	0.0 b	-2.5 c
	|e|	3.6 b	3.5 b	3.3 b	3.4 b	4.7 a
	SD	3.1	2.8	2.7	2.5	3.3

[+] Within each statistic, means followed by the same letter are not significantly different at $\alpha = 0.05$ level using DMRT.

Table D3.2. Mean error (e), mean absolute errors (|e|), and standard deviation of absolute errors (SD) in days for predicted minus actual dates of physiological maturity in test years. Data are means of nine CRD, three planting dates per year, and 7 years (n = 189).

	Thermal Models				Mixed Models[±]				Calendar
Statistic	GDU	MGDU	HS	FT	GDU	MGDU	HS	FT	Days
				Indiana					
e	7.4a[#]	4.0b	5.4b	2.6d	0.8e	0.3e	0.3e	-0.5e	-3.8f
|e|	11.0a	7.3b	8.2b	5.9c	3.4d	3.3d	3.2d	3.3d	6.7c
SD	8.6	5.8	7.4	5.2	2.7	2.6	2.6	2.7	4.5
				Iowa					
e	4.6a	1.6b	3.7a	1.2b	-0.4c	-0.8c	-0.4c	-1.1c	-3.7d
|e|	11.0a	8.0b	9.8b	7.8b	5.3c	5.2c	4.9c	4.9c	6.4c
SD	9.4	6.9	9.1	6.7	4.0	3.9	3.6	3.5	4.7

[+] The mixed models predict physiological maturity date in each CRD by using the thermal models (Table D3.1) to estimate silking date and then adding the mean number of days from silking to physiological maturity for each CRD.

[#] Within each statistic, means followed by the same letter are not significantly different at $\alpha = 0.05$ level using DMRT.

D.4. Effects of Management Practices on the Reflectance of Corn
and Soybean Canopies.
J. P. Ward and C. S. T. Daughtry

As the world's need for food has increased, the demand for fast
and accurate information on crop production has intensified. The
application of remote sensing to agriculture has included research on
identification of crops, detection of crop stresses, and prediction of
crop yields. Methods for determining the cultivar, plant population,
row width, planting date, and soil type of a corn or soybean field could
prove to be valuable in interpreting reflectance measurements and more
importantly in predicting crop yields.

Spectral and agronomic measurements were acquired from corn and
soybean plots at the Purdue Agronomy Farm during the 1980 growing
season. Forty-eight soybean and 36 corn plots were observed to study
the effect of soil type, planting date, row width, plant population and
cultivar on yield and reflectance. A Landsat band radiometer was used
to measure spectral reflectance measurements in four bands (0.5-0.6,
0.6-0.7, 0.7-0.8, and 0.8-1.1 μm).

For the Purdue Agronomy Farm, all of the management practices
chosen could be distinguished on the basis of reflectance at some point
during the season. The reflectance factors of individual bands were
best for identifying soil type but the greenness transformation worked
best for separating all the other management practices. Percent ground
cover, leaf area index, and development stage explained most of the
variation in reflectance associated with planting date, population, row
spacing, and cultivar.

A second experiment was conducted to investigate the applicability
of using Landsat MSS data to detect different management practices in
commercial fields. For the commercial fields studied, differences in
planting dates greater than approximately two weeks and differences in
row spacing (solid-seeded versus wide rows) could be identified using
the greenness transformation.

Large differences in management practices do occur among regions
in the United States since they are confounded with such factors as
weather, soil fertility, and length of the growing season. Thus it
would be difficult to ascertain the causes of variations in reflectance
between two fields of the same crop in different regions of the country.

The synoptic view of the earth available with Landsat data could
potentially be used to stratify crop production regions of country in to
relatively homogeneous areas. Spectral data from individual fields
could then be used to identify subtle changes in management practices
which contribute to variability in yields within each stratum. Thus
crop production could be estimated using a sample of as many fields as
necessary to obtain reliable results.

III. SUMMARY OF TECHNICAL ASSISTANCE PROVIDED TO NASA/JSC

* Developed and tested an indirect calibration procedure for the multiband radiometer mounted on a NASA helicopter in 1983.

* Developed and evaluated a temperature correction for the PbS detectors in the airborne radiometer in 1984. Recalibrated all spectral data with new temperature correction algorithm.

* Trained two LEMSCO technicians to operate the ground-based radiometer for the indirect calibration procedure in 1983 and 1984.

* Participated in selection of test sites within the Superior National Forest (SNF) in 1983.

* Operated the optical and microwave instruments onboard the NASA/JSC helicopter in the SNF during July, August, and September of 1984.

* Participated in post-season calibration of the C-band scatterometer on the NASA/JSC helicopter in 1984.

* Designed specialized equipment and acquired in situ measurements of understory reflectance and overstory transmittance in several test sites in SNF during 1983 and 1984.

* Preprocessed and calibrated all of the multiband radiometer data from the COVER experiment in SNF in 1983 and 1984.

* Constructed, prepared, and painted 18 2x2-foot and 20 4x4-foot $BaSO_4$ reference panels. Shipped panels to researchers at the following institutions:

CIMMYT	South Dakota State Univ
Kansas State University	Texas A & M University
NASA	University of Michigan
Ames Research Center	University of Minnesota
Earth Resources Lab	University of Nebraska
Johnson Space Center	University of New Mexico
North Dakota State	USDA/ARS
Oregon State University	Bushland
Purdue University	Lubbock
Rutgers	Phoenix

* Repainted (as necessary), measured the angular spectral properties of 20 reference panels and distributed the data to researchers in 1984 and 1985.

* Conducted field research workshops at Purdue University, NASA/Goddard Space Flight Center and CIMMYT in 1982 and 1983.

* Visited most field research sites in 1983 to review data acquisition
procedures. Provided additional support via telephone and mail as
needed from 1982 through 1985.

* Updated and maintained the vegetation and soil field research data
base. Distributed copies of portions of the data base to the following
researchers at the request of NASA during 1982 through 1985:

    Alabama A & M University, Huntsville, AL
    Canada Centre for Remote Sensing, Ottawa, Canada
    CIMMYT, Mexico City, Mexico
    Colorado State University, Fort Collins, CO
    ERIM, Ann Arbor, MI
    Goddard Institute of Space Studies, New York, NY
    Kansas State University, Manhatten, KS
    Los Alamos National Laboratory, Los Alamos, NM
    National Aerospace Laboratory, Amsterdam, The Netherlands
    NASA
       Ames Research Center, Moffett Field, CA
       Earth Resources Laboratory, NSTL, MS
       Goddard Space Flight Center, Greenbelt, MD
       Johnson Space Center, Houston, TX
    NOAA NESDIS, Washington, DC
    North Dakota State University, Fargo ND
    Oregon State University, Corvallis, OR
    Pan American University, Edinburg, TX
    Phillips Petroleum Company, Bartesville, OK
    Purdue University, West Lafayette, IN
    SCIPAR, Inc., Williamsville, NY
    South Dakota State University, Brookings, SD
    State University of New York, Binghamton and Syracuse, NY
    Texas A & M University, College Station and Lubbock, TX
    University of Arizona, Tucson, AZ
    University of California, Santa Barbara, CA
    University of Hawaii, Honolulu, HI
    University of Kansas, Lawrence, KS
    University of Michigan, Ann Arbor, MI
    University of Minnesota, St. Paul, MN
    University of Nebraska, Lincoln, NE
    University of New Mexico, Albuquerque, NM
    University of Wisconsin, Madison, WI
    USDA/ARS
       Bushland
       Phoenix
       Weslaco

* Calibrated the Barnes 12-1000 radiometers for radiance measurements.
Provided techniques and data for converting reference panel voltages in
in-band solar irradiance.

* Developed calibration procedures for the thermal band of the Barnes
12-1000 radiometer. Calibrated the thermal data from the radiometers
used in the SNF in 1983 and 1984.

* Designed, fabricated, and installed adapters to reduce the fields of view (FOV) of the Barnes 12-1000 radiometers to either 6 or 10 degrees.

* Developed and tested procedures to package and ship samples of leaves, twigs, and bark from the SNF to Purdue and JSC with minimal changes in their spectral properties in 1983.

* Measured spectral reflectance and transmittance of 648 aspen leaves and 216, 30, and 20 samples of needles of black spruce, jack pine, and red pine, respectively, from SNF in 1983. Spectral properties were also measured for more than 50 samples of bark and twigs from aspen and black spruce in 1983.

* Compared and analyzed directional-hemispherical measurements of reflectance and transmittance from Purdue's LICOR spectroradiometer and JSC's Cary-14 spectroradiometer in 1983.

IV. PUBLICATIONS BY STAFF AT PURDUE

The following lists of papers, reports, and abstracts are the results of research wholly supported or at least partially supported by this NASA contract. 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.

A. Refereed Papers

Ahlrichs, J. S. and M. E. Bauer. 1983. Relation of agronomic and mulispectral reflectance characteristics of spring wheat. Agron. J. 75:987-993.

Bauer, M. E. 1985. Spectral inputs to crop identification and condition assessment. IEEE Proceedings 73:1071-1085. Special issue on "Perceiving Earth's Resources from Space".

Bauer, M. E., C. S. T. Daughtry, L. L. Biehl, E. T. Kanemasu, F. G. Hall. 1985. Field spectroscopy of agricultural crops. IEEE Trans. Geosci. Remote Sens. GE-24:65-75. (invited paper)

Baumgardner, M. F., L. F. Silva, L. L. Biehl, and E. R. Stoner. 1985. Reflectance properties of soils. Advances in Agronomy 38:1-44.

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Daughtry, C. S. T., J. E. Cochran, and S. E. Hollinger. 1984. Estimating silking and maturity dates of corn for large areas. Agron. J. 76:415-420.

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Grant, L., C. S. T. Daughtry, and V. C. Vanderbilt. Variation in the polarized leaf reflectance of Sorghum bicolor. (Submitted to Remote Sens. Environ.).

Hinzman, L. D., M. E. Bauer, and C. S. T. Daughtry. 1985. Effects of nitrogen fertilization on growth and reflectance characteristics of winter wheat canopies. Remote Sens. Environ. 19:47-61.

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Ranson, K. J., L. L. Biehl, M. E. Bauer, and C. S. T. Daughtry. 1985. Effects of sun and view angles on reflectance factor of corn canopies. Remote Sens. Environ. 18:147-161.

Ranson, K. J. and C. S. T. Daughtry. 1986. Scene shadow effects on multispectral response from small balsam fir canopies. IEEE Trans. Geosci. Remote Sensing. (submitted)

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V. PUBLICATIONS BY OTHER RESEARCHERS

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