The Spectral-Agronomic Multisite-Multicrop Analyses (SAMMA) Project

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Abstract Numerous individual investigators around the world have made seasonal spectral reflectance measurements on one or more crop canopies and characterized their leaf area index, dry matter, light interception and other characteristics. However, the data have never been studied to determine whether common functional relationships exist between the spectral, agronomic, and light interception observations within crops across years and geographic locations, or whether the relationships differ among crops. General relationships are needed as inputs to crop simulation models that utilize remotely sensed information, and to calibrate empirical models that relate spectral observations to biological and economic yield. To answer the questions posed, some 17 U.S. researchers have pooled the data from over 50 experiments for wheat, cotton, maize, sunflower, soybean, grain sorghum and alfalfa. We describe the experiments involved, the data format, analytical procedures recommended, and preliminary results. Hopefully, the paper will encourage additional workers to similarly analyze data available to them.

Individual investigators the world over have made seasonal spectral reflectance measurements of crops and characterized the canopies agronomically (leaf area index, (LAI); aboveground fresh and dry phytomass (FM,DM); leaf fresh mass (LFM) and dry mass (LM). Usually, yields and phenological observations were also made. In some cases, intercepted or absorbed photosynthetically active radiation (IPAR, APAR), evapotranspiration or water use (ET), and canopy temperature observations were made. Often, more than one crop has been studied in a given year at a site and experiments with different objectives have been conducted over a period of years.

In this paper we describe a project underway in the United States to pool data from such experiments and uniformly analyze them in order to (a) develop functional relations between vegetation indices (VI) and crop agronomic characteristics (LAI,DM,LM) within crops by experiments, and test for commonality among years, experiments, and locations, and (b) investigate relationships among IPAR or APAR, LAI, DM and yield across time and location within and among crops. The premises of the effort were that (1) enough observations had been made on wheat (Triticum aestivum L.), maize (Zea mays L.), grain sorghum (Sorghum bicolor Moench), soybean (Glycine max Merr.), and cotton (Gossypium hirsutum L.) to make intercomparisons of results among crops and locations timely, and (2) progress would be made faster and less expensively by further analyzing existing data than by conducting more experiments.

If successful this project will provide specific VI-agronomic characteristic relations for several crops. Such relations are presently lacking. To describe the nature and scope of the effort, the title, Spectral-Agronomic, Multisite-Multicrop Analyses (SAMMA) was given the project.

In the following sections we describe how the experiments and experimenters were identified, possible sources of variation to consider and ways to deal with them, data format adopted, division of labor, analytical procedures recommended, and exemplary results.

1. Identification of Experiments and Experimenters

Candidate research participants were identified from their publications reporting single site results, and from their known participation in ground measurements in support of any of the following: the Large Area Crop Inventory Experiment (LACIE) (MacDonald and Hall, 1980); the Wheat Yield

Project of the Agricultural Research Service, USDA (Willis and Grable, 1985), and the multiagency effort called Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS). Most of the prospective participants were active in the Great Plains regional committee called the Remote Sensing Coordinating Committee which met annually from 1975 through 1987.

The senior author wrote the prospective participants, explained the purpose of the project, invited their participation, and enclosed copies of a one-page form for documenting available experiments. The form provided for identifying the investigators; the local name of the experiment; the treatments, years, and seasons of the experiments; crops used including cultivar names; latitude and longitude (to the nearest 0.1 degree) of the experimental site; a checklist of plant (height, phenology), canopy (LAI, FM, DM, FLM, LM, IPAR, APAR, temperature (TC)), water balance, and soil property (upper and lower plant available water limits, wet and dry reflectance factor) measurements that were made; the frequency of measurements (diurnal, daily, weekly, irregular periodic); names of the soil series and their universal taxonomic names; and, the specific instruments used for canopy temperature, reflectance, and light interception.

A list of candidate experiments was compiled, by crops, in the chronological order the experiment survey responses were returned. The resulting summary for sorghum is shown as Table 1.

At a follow-up meeting in October, 1985, attended by 14 scientists representing 9 research locations (Table 2), the experiments were rated by the location representatives into the categories:

(1) Can complete raw data (plant growth and agronomic characterization, canopy spectral, weather, water balance, soil, and time of observation) summarization within 6 months without additional funding.

(2) Can complete summarization within 6 months after funding is obtained.

(3) Can summarize data within 1 1/2 years, but requires additional resources.

The number of experiments in each category by crop was:

	COR	COT	SOR	SOY	SUN	WHT	ALF	TOTALS
Cat.1	5	7	4	2	1	5	1	25
Cat.2	-	-	3	3	1	5	-	12
Cat.3	1	1	1	1	2	12	1	19
	6	8	8	6	4	22	2	56

Thus 37 of the experiments fell into the combined categories 1 and 2. As shown, there were at least 5 experiments for each of the crops corn (COR), cotton (COT), sorghum (SOR), soybean (SOY), and wheat (WHT). Subsequently, some scientists and locations have been unable to participate because supporting funds have been lacking, but the effort is proceeding using the data sets that are being provided.

2. Division of Labor

Within crop coordinators were chosen at the 1985 meeting as follows:
Corn-Stephan Maas, ARS-USDA, Weslaco, Tx
Cotton-Don Wanjura, ARS-USDA, Lubbock, Tx
Sorghum-Terry Howell, ARS-USDA, Bushland, Tx
Soybean-Craig Daughtry, ARS-USDA, Beltsville, Md (at Purdue University when chosen)
Sunflower-Jean Steiner, ARS-USDA, Bushland, Tx
Wheat-Jerry Hatfield, ARS-USDA, Lubbock, Tx and Craig Wiegand, ARS-USDA, Weslaco, Tx

The division of labor among individual locations, crop coordinators, and the overall coordinator (senior author of this paper) developed as follows:

Individual Scientists-Proceed with planned analyses and uses of location data and participate in SAMMA effort by also (a) providing standardized graphs (Table 3) to the appropriate crop coordinators (by mid-1986), (b) using the graphs to help identify outliers and sources of within location variation in the observations among crops and years, and (c) summarizing data to a uniform format (discussed later) and forward them on a continuing basis to the appropriate crop coordinator(s) along with pertinent observations about data quality as affected by weather events, instrument functioning, and sampling procedures. Location scientists are responsible for the order and the rate at which experiments are summarized. As of April, 1987, part or all graphs had been prepared for 38 experiments, a figure that includes experiments for wheat added since 1985.

Crop Coordinators-Examine the graphs to identify consistencies in shape and slopes of relations among locations and the behavior of various vegetation indices (VI) among sensor systems and locations. Use physical and biophysical relationships (Asrar, et al., 1984; Lang and Yueqin, 1985; Sellers, 1987; Choudhury, 1987) and relations previously reported to suggest worthwhile comparisons. Consult with individual scientists and the other crop coordinators to standardize phenologic scales, data smoothing procedures, data format, acronyms, equation forms, specific comparisons and statistics to use... At annual meetings, they should lead discussions comparing relationships and consistencies/inconsistencies among locations. Responsible for within crop analyses and jointly with location scientists who contributed, they author publication of intracrop, interlocation analyses.

Project Coordinator-Provides general leadership including developing meeting agendas and presiding, producing and communicating minutes of discussions and meetings, setting goals and deadlines, providing an overview and encouragement, defining and performing analyses, and summarizing and documenting intercrop analyses.

3. Data Formats

The data formats of a regional project on water-nitrogen effects on water use efficiency of wheat (Reginato, et al., 1988) were adapted by the junior author and a 25-page guide that provided line and field for entry of data by treatments within experiments, defined the units to be used, and provided for entry by day of year of the following 12 different types of data: experiment and site description, plant population, plant phenology, plant biomass, plant economic yield, light interception (daily), light interception (diurnal), canopy reflectance factor or radiance, canopy temperature (daily), canopy temperature (diurnal), soil water content, and weather observations. Treatments were coded by cultivar, planting date (year and day of year), population (plants/m^2), fertility (element and amount in Kg/ha, e.g., N200), row spacing (meters), row direction (azimuth degrees to the right of north-south which has a reference azimuth of zero degrees), year of experiment (based on calendar year of harvest), and irrigation and other cultural variables. Field space was left for comments such as maturity class of soybean cultivars grown, type of wheat (winter, spring, durum) and leaf display descriptions and for measurements such as plant height and percent cover that were taken in some experiments.

4. Sources of Variation and Ways of Dealing with Them

Numerous sources of variation exist among experiments, including differences in (1) sensor systems (Table 4) and calibrations (design, sensitivity, wavelength intervals, instantaneous field of view (IFOV)), (2) sampling procedures and measurement techniques (height of instruments above the canopy, number of plants and repetitions of samples for characterizing the canopies), (3) bidirectional (sun and sensor positions) and atmospheric (turbidity, diffuse and specular energy streams, water content of atmosphere, cloudiness) effects, (4) nongreen and nontranspiring plant parts, shadows, and soil in the IFOV of canopy reflectance, transmittance, and temperature sensors, and presence of dew, (5) intercultivar and species genetic differences in leaf angle, leaf dimensions, heliotropism, tillering capacity, phenology..., (6) growing season and climatic differences due to latitude and elevation (daylength, air and soil temperature, saturation deficit, solar radiation), (7) cultural practices (fertilization, irrigation, populations, row spacing), (8) soil differences (reflectance factor, roughness, moisture content, depth of rooting, water holding capacity), (9) stresses both apparent and incipient (weather related--sub- or super-optimal air and soil temperatures, low insolation (clouds)); excess or deficit precipitation; quality of seedbed preparation that affected plant stands and their uniformity within plots; insects; nematodes; foliar diseases; herbicide residues...; and, (10) irregular distribution of observations during the life cycle of the crop (too few during early vegetative development, duration into senescence).

To accomodate (1) and (2), the visible red (RED) and near-infrared (NIR) bands common to all instruments are being emphasized and measurements of reflectance are expressed as reflectance factors. The observations permit the normalized difference (ND), simple ratio (SR) and perpendicular (PVI) vegetation indices, defined by ND=(RIR-RED)/(RIR+RED), SR=NIR/RED, and PVI_{Exo}=0.647(MSS7) -0.763(MSS5) -2.0 to be computed. Data can be segregated by systems used, such as EXOTECH, BARNES modular multiband radiometer, and Mark II (Table 4), but some data sets could be deleted if circumstantial evidence merits it.

To accomodate source of variation (3), all data except canopy temperature use only nadir view observations, observations were made mostly under clear sky conditions, and practically all data are from handheld or boom-mounted (ground) systems. The few top of atmosphere (satellite) observations have been adjusted by satellite calibration coefficients and are also expressed as reflectance factor. But sun position was unique for each subset of observations. It was recommended that when LAI observations are paired with VI and IPAR observations, LAI be divided by the cosine of the solar zenith angle at the specific times the refectance factor (cos Z1) and IPAR (cos Z2) observations were made (Wiegand and Richardson, 1987). The adjustment applies in the solar zenith range from 0 to 60 degrees (Richardson and Wiegand, 1986). The debugged[a/] algorithm of Walraven (1978) was provided the participants for calculating the solar elevation angle (zenith angle = 90 - elevation angle) and solar azimuth angle at any time of observation (year, day of year, hour and minute) for a specified latitude and longitude. (All experimenters had automatically logged the time of observation to the nearest minute.)

To help with partial canopy cover situations, when proportions of sunlit and shadowed soil are important, the participants were shown how to calculate the perpendicular vegetation index, PVI, (Richardson and Wiegand, 1977; Jackson, et al., 1980) and n-space greenness, GRn, (Jackson, 1983) and were given Apple II Basic and Fortran IV programs for the latter. Huete (1987) showed that ND and SR were sensitive to line of sight sunlit and shaded soil in the IFOV at partial plant cover whereas PVI was nearly constant across sun angles and soil reflectances. All three vegetation indices increased with solar zenith angle in agreement with a greater probability of incident specular light striking leaves as it passes through the canopy from increasingly off nadir positions. In summary, the insensitivity of PVI and GRn to soil background reflectance and changing shadowing at partial plant cover commend them for analysis of multisite, multisoil, multiseason, and multicrop data sets influenced by sources of variation identified in consideration (4).

To deal with nonliving phytomass in the data, plans are to divide the VI, IPAR, and LAI observations into seasonal portions up to and after maximum LAI (LAIm) when data permit. Then separate relations for the periods preceding and following LAIm can be developed for LAI versus IPAR and VI, and between VI and IPAR. This procedure has appeal because previous results show that photosynthetically inactive plant parts shade the light transmission sensor,

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[a/] Prepared by A. J. Richardson and debugged by J. L. Hatfield. Included in Handout Materials, SAMMA Discussions, Lubbock, Tx, October 29 - 31, 1985, 45p.

causing erroneously high IPAR and APAR estimates from LAI during reproduction and maturation growth phases whereas there is little hysteresis between VI and LAI until late in the season (Figure 1). Sources of variation (5) through (9) constitute the uncontrollable variation among the experiments. The comments provided by the investigators could be consulted when questions arise about the data. Daily air temperature data, when provided, can also be expressed in thermal time units and be graphed versus LAI and DM to intercompare growth rates and growth periods among experiments. Reported dates of rainfall and irrigations infer times when the soil was wet. The volume of data involved, however, means the crop coordinators will rely mostly on data editing done by the locations and on comment statements within the formatted data sets.

5. Data Smoothing

Participating scientists agreed that treatment mean raw observation data be entered into the various formats. That is, no smoothing was to be done on data submitted to the crop coordinators. But the various plant and spectral observations were made on a staggered and irregular schedule so that it is necessary to interpolate between measurements to pair data for analysis on the same date. Smoothing procedures such as cubic spline, polynomial, and moving-average polynomial fit the data to a continuous path through the data versus day of year, and estimate a daily value for each type of data smoothed. In the end, it was left to individual crop coordinators to use the smoothing procedure(s) familiar to them and available on the software packages at their locations.

6. Analysis Procedures

An exemplary data analysis objective is to determine whether the APAR versus LAI relations are consistent within crops and among locations. To do that, it is necessary to use closely similar wavebands, preprocess the data by procedures that take solar zenith angle and other considerations deemed important into account, and analyze the data by the same equation forms. If that is done, the objective can be accomplished by determining whether the equation coefficients are statistically alike or different. By the summer of 1987, progress was such that comparisons could begin.

The following three parameter model was proposed for fitting the APAR versus LAI data:

$$\begin{aligned} APAR &= (1 - Ri)(1 - Ti) \\ &= (1 - Ri)(IPARi) \\ &= (1 - Ri)(1 - Ai\ e^{-Ki(LAI/\cos Z2)}) \\ &= Ci(1 - Ai\ e^{-Ki(LAI/\cos Z2)}) \end{aligned}$$

wherein

Ri = reflectance in PAR wavelengths normalized to incident PAR flux (measured with a downward looking line quantum sensor (LQS) held about 30 cm above the canopy)

Ti = transmittance in PAR wavelengths normalized to incident PAR flux (measured with an upward looking LQS beneath the canopy),

(1 - Ri) = Ci = the asymptotic value of (1 - Ri) at large leaf area index, LAI, corresponding to infinite reflectance [In an energy balance, it is also the net downward flux of light available for interception at large LAI],

Ai = the PAR transmission intercept at LAI = 0 (Can be estimated graphically from plots of T on log scale versus LAI on linear scale),

Ki = the extinction coefficient,

Cos Z2 = cosine of solar zenith angle when Ri and Ti were simultaneously measured, and

i = a treatment identifier.

The asymptotic value of reflectance in the PAR wavelengths is about 4% so that (1 - Ri) can be expected to be close to 0.96. The coefficient Ai is theoretically 1.0 but in data from field experiments it ranges from 0.8 to 1.2 for the vegetative development period. Ai can be considered a measure of how much the measurement conditions deviated from the lateral uniformity assumption. If data sets are divided into seasonal portions emergence through LAIm and LAIm to full senescence, then during the senescence portion of the data, Ai is a combined measure of the lateral uniformity deviation and the amount of nonphotosynthetic tissue shading the transmitted light sensor. Ki, the extinction coefficient, is dependent on leaf display and sun position.

The nonlinear least-squares regression procedure (PROC NLIN) of the SAS statistical package (SAS, 1979) can be used to analyze the data. In this iterative procedure, starting values must be specified for all parameters in the model. Beginning values of 1.0 for both A and C are logical, while studies with many different crops have produced extinction coefficients between 0.4 and 0.9 making 0.6 or 0.7 a reasonable first estimate.

The data are input by experiment (or treatments within experiments), and the program calculates and prints out the least squares estimates of each parameter of the full and reduced models (Table 5) for each experiment (or treatment within an experiment) along with their standard errors and 95% confidence intervals, correlation matrix of parameters, and summary statistics needed to perform an asymptotic F test to test hypotheses (a), (b), and (c) in Table 5. Full details were provided the participants in Handout Materials.

But data for LAI and VI are much more numerous than for APAR and LAI, and need to be studied. The curves for VI as a function of LAI begin at the value for bare soil at LAI=0 and proceed to asymptotically limiting VI values at high LAI in the same way IPAR and APAR do. They also have a characteristic slope, or absorption-scattering coefficient, analogous to the extinction coefficient in the APAR versus LAI relation. Consequently, we can apply an equation of the same form,

$$VI = Fi\ (1 - Di\ e^{-Ei(LAI/\cos Z)})$$

For ND, the asymptotically limiting ND or Fi is approximately 0.9, Di is approximately 0.8 = (1 - NDs) where NDs = 0.2 is the ND of bare soil, and the exponent Ei, an absorption-scattering coefficient will approach unity. Thus in the iterative fitting procedure, initial estimates of 0.9 for Fi, 0.80 for Di, and 0.8 or 0.9 for Ei are suggested if ND is the VI being used. Greenness (GRn), SR, and PVI would have different parameter values.

As with APAR data, it can be determined whether Fi, Di, amd Ei are common among treatments within an experiment, and, if so, the appropriate value of the parameters for individual treatments and the experiment as a whole. Then data from different experiments can be pooled and it can be determined whether the parameters differ or not among experiments. In this case the treatment identifier becomes an experiment identifier.

The seasonal data can and should be separated into pre-LAIm and post-LAIm subsets and the data fitted separately if adequate data were taken in the two periods.

More theoretically based tests can also be conducted. Kanemasu[b/] proposed that, for wheat, to a good approximation, APAR versus ND is linear and that the APAR versus VI relation can be inverted to estimate LAI. The equation being inverted (Asrar, et al., 1984) is

$$LAI = \overline{\ln(1-p)} \cdot \frac{1}{\overline{S}'}$$

where $\overline{\ln\ (1-p)}$ is the arithmetic mean of the natural logarithm of the predicted PAR transmission, $\overline{S}'$ is the mean leaf angular shape coefficient which depends on solar zenith angle, and p is interception.

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b/Minutes SAMMA meeting, Manhattan, Ks, April 21, 1987.

The inversion approach may not be as appropriate for other crops as for wheat. Because wheat is planted in closely spaced rows, the assumption of lateral uniformity is met at much lower LAI than for crops with wider row spacing, and leaf display is approximately spherical. Also, the theory developed for canopy interception in the PAR wavelengths was extended to canopy absorption (APAR) since the two do not differ very much.

The data also lend themselves readily to spectral components analysis (Wiegand and Richardson, 1987).

7. Exemplary Results

Figure 1 shows that for one wheat plot (unpublished relation from the data set reported by Pinter et al. (1981; SAMMA data set WHT-21) LAI estimates for wheat during maturation agreed with those during vegetative development down to LAI=2 whereas APAR estimates from LAI agreed only down to LAI=4 (Hipps, et al., 1983).

Figure 2 displays the APAR versus LAI/Cos Z data for cotton grown at Weslaco, Tx, and submitted to 1 and 2 applications of a growth regulator (MC, MC2), no growth regulator and not thinned (NT), and no growth regulator but thinned to one-half stand (<NT). The nonlinear SAS procedure was applied and it was learned that treatments did not cause the parameters to differ so that the fully reduced model form (footnote d, Table 5) was appropriate, and C, A, and B were, respectively, 1.019 $\pm$ 0.016, 0.922 $\pm$ 0.009, and 0.469 $\pm$ 0.020.

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Table 1. Grain sorghum experiments available for uniform analysis with checklist of canopy, plant, sun position, weather, water use, and soil information observed or known.

CROP: SORGHUM		CANOPY[1/]			PLANTS[2/]							SOLAR ZN & AZ			WEATHER[3/]					H_2O BAL		SOIL[4/]		
INVESTIGATOR(S)	YR	VI	TC	IPAR	LAI	AGDM	PS	POP	PC	YIELD	RL	DOY	HR & MIN	LAT & LON	TA	SR	PPT	SD	WS	YES	NO	RF	UL & LL	OBJECTIVE(S)
1. Steiner	'83,'84	X	-	X	X	X	X	X	-	X	-	X	X	-	X	X	-	X	X	X		-	X	IPAR as F (planting config.) H_2O bal. & growth as F (above)
2. Wiegand, Richardson Gerbermann	'73-'78	X	-	-	X	-	X	X	X	-	-	X	X	X	X	X	-	-	-		X	-	-	Relate mss data to GRD truth spectral components analysis.
3. Wanjura, Hatfield	'84,'85	X	-	X	X	X	-	X	X	-	-	X	X	X	-	-	-	-	-	-	-	-	-	Canopy structure relation to R, T, IPAR. Hourly spectra 4 crops, 3 dates
4. Wanjura	'82-'85	X	-	-	X	X	X	X	X	X	-	X	X	X	X	X	X	X	-		X	X	X	Estimate biomass, GS, water/temp. stress, ID spectrally
5. Kanemasu	'83	X	X	X	X	X	X	X	-	X	X	X	X	X	X	X	X	X	?	X	-	X	X	Spectral characterization of several crops under same environ.
6. Howell, Musick Steiner, Dusek	'85	X	X	X	X	X	X	X	X	-	-	X	X	X	X	X	X	-	-	X	-	X	-	Spectral effects of pop and spacing and APAR vs VI
7. Musick, Dusek	'83	X	X	X	X	X	X	X	X	X	-	X	X	X	X	X	X	-	-	X	-	X	-	Repeatability of VI's and as model inputs. Extend data range for water stress
8. Musick, Dusek	'81,'82	X	X	-	X	X	X	X	X	-	-	X	X	X	X	X	X	-	-	X	-	X	-	Develop VI to estimate AGDM, LAI, PC. Seasonal spectra vs stress periods

1/CANOPY (l to r): vegetation index, canopy temperature, intercepted PAR.
2/PLANTS (l to r): leaf area index, above grd. wet/dry phytomass, phenological stage, population, percent cover, yield, leaf reflectance.
3/WEATHER (l to r): max. and min. daily temp., solar radiation, precipitation, saturation deficit, windspeed.
4/SOIL (l to r): wet and dry reflectance factor, upper and lower limits of plant available water.

Table 2. Geographic distribution of SAMMA Project experiment locations, the crops studied at each location, and the names of the participating scientists.

Location	Latitude (degrees north)	Longitude (degrees west)	Elevation (m)	Crops	Scientists
Purdue University, West Lafayette, IN	40.5	87.0		COR, SOY	C. S. T. Daughtry K. Gallo
University of Nebraska, Lincoln, NB	41.6	100.8		COR, SOY, WHT	B. L. Blad
Mandan, ND	47.0	101.0		WHT	A. Bauer
Sidney, MT	47.8	104.2		WHT	J. K. Aase
Kansas State University, Manhattan, KS	39.1	96.6		COR SOR SUN WHT	E. T. Kanemasu G. Asrar
Phoenix, Az	33.4	112.0		WHT	R. D. Jackson P. J. Pinter, Jr
Bushland, TX	35.2	102.2	1120	COR, SOR, SOY, SUN, WHT	D. Dusek T. A. Howell J. L. Steiner
Lubbock, TX	33.4	101.5	988	COT, SOR, SOY, SUN, WHT	J. L. Hatfield D. F. Wanjura
Weslaco, TX	26.2	98.0	21	COT, COR, SOR, WHT	S. J. Maas A. J. Richardson C. L. Wiegand

Table 3. Dependent (ordinate) and independent (abscissa) variables, anticipated ranges, and size of graphs to be uniformly produced for overlaying.

Graph No.	Dependent Variable	Range	Full Scale	Indepen. Variable	Scale
1.	ND	0-1.0	12.7cm	LAI	1.9cm per LAI unit
2.	RIR/RED	0-30	"	"	"
3.	GR	-18 to +72	"	"	"
4.	RIR	0-75	"	"	"
5.	RED	0-15	"	"	"
6.	IPAR	0-1.2	"	"	"
7.	LAI/cosZ	As needed	"	"	"

Table 4. Band and wavelength intervals (WLI) of spectroradiometric systems used in the SAMMA Project along with additional systems (TM, TMS, HRV) described for comparison.

EXO,[a/] MSS	WLI	MMR[b/]	WLI	MK[c/]	WLI	TM,[d/] TMS	WLI	HRV [e/]	WLI
(band)	(um)	(band)	(um)	(band)	(um)	(band)	(um)	(band)	(um)
		1	.45-.52			1	.45-.52		
1	.50-.60	2	.52-.60			2	.52-.60	1	.50-.59
2	.60-.70	3	.63-.69	1	.63-.69	3	.63-.69	2	.61-.68
3	.70-.80							Pan	.51-.73
4	.80-1.1	4	.76-.90	2	.76-.90	4	.76-.90	3	.79-.89
		5	1.55-1.75			5	1.55-1.75		
		6	2.08-2.35			7	2.08-2.35		
		7	10.4-12.5			6	10.4-12.5		
		8	1.15-1.30						

[a/] EXOTECH, LANDSAT multispectral scanner; [b/] BARNES modular multiband radiometer; [c/] Mark II; [d/] LANDSAT thematic mapper, Thematic mapper simulator (aircraft scanner); [e/] SPOT high resolution visible.

Table 5. Hypotheses tested, model forms compared, and questions answered in analyzing APAR versus LAI among treatments or experiments.

Hypothesis tested	Model Forms Compared	Question Answered
(a) $C_1=C_2=C_3=C_4=C$	(1) versus (2) Ai Bi Ci vs C Ai Bi	Can the treatments or experiments be represented by a single value of C?
(b) Ci=C, $A_1=A_2=A_3=A_4=A$	(1) versus (3) Ai Bi Ci vs C A Bi	Can the treatments be represented by a single value of C and A?
(c) Ci=C, Ai=A $B1=B^2=B^3=B^4=B$	(1) versus (4) Ai Bi Ci vs C A B	Can the treatments be represented by a single value of C, A, and B?

i=1 .... t, number of treatments being compared.

(1) Full model, $APAR=Ci[1-Aie^{-Ki(LAI/cosZ2)}]$

(2) Reduced model, $APAR=C[1-Aie^{-Ki(LAI/cosZ2)}]$

(3) Reduced model, $APAR=C[1-Ae^{-Ki(LAI/cosZ2)}]$

(4) Reduced model, $APAR=C[1-Ae^{-K(LAI/cosZ2)}]$

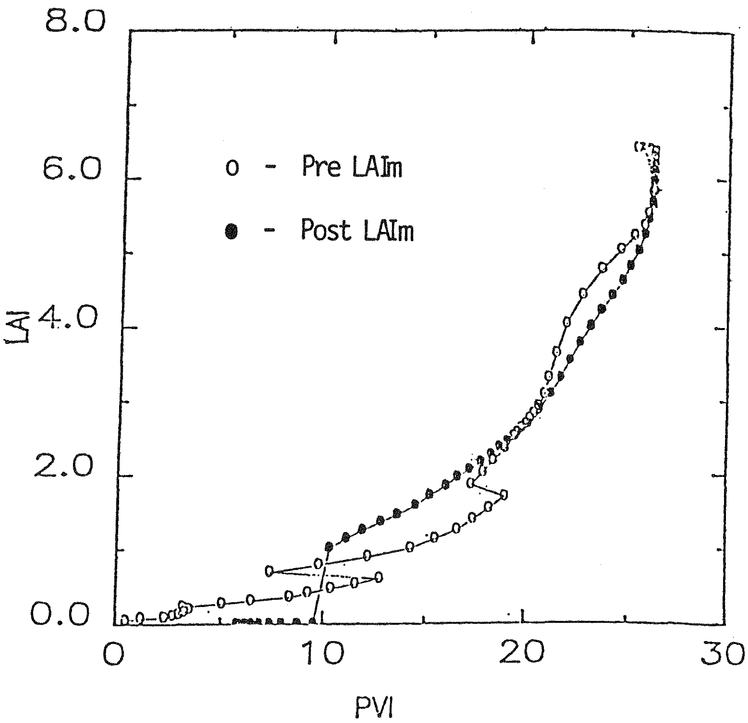

Figure 1. PVI versus LAI for one wheat plot at Phoenix, Az. (Data set SAMMA WHT-21)

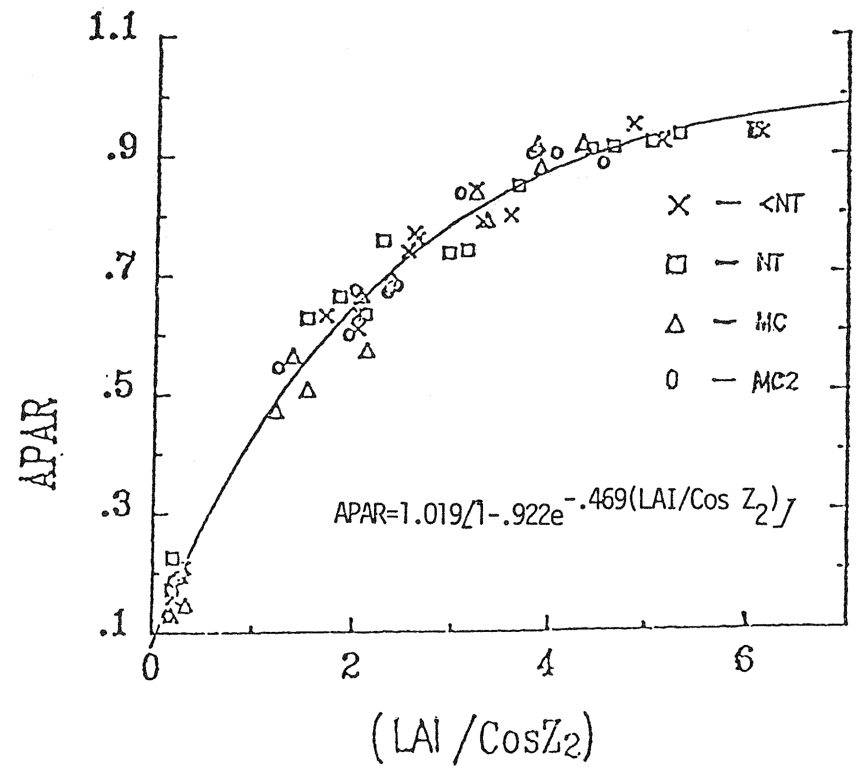

Figure 2. APAR versus (LAI/Cos Z_2) for cotton grown at Weslaco, Tx and fit by three parameter model discussed in text. (Data set SAMMA COT-2)