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A Seasonal Verification of the Suits Spectral Reflectance Model for Wheat

The seasonal average coefficient of determination was 0.88 between the Suits spectral bidirectional reflectance model and field-measured reflectance data.

Introduction

Application of Landsat multispectral scanner data to agricultural problems, such as crop identification, crop yield, and the identification of crop disease, has prompted studies on the interaction of solar radiation with crop canopies. Remotely sensed multispectral radiation has many uncontrolled and non-reproducible parameters. A mathematical modeling effort is required in order to understand the interplay of variables in vegetation reflectance and atmospheric transmission. This paper is directed toward the verification of a mathematical model of the bidirectional reflectance of a wheat canopy. To this end, several experimental studies are now in progress. A very extensive program of this type is the Large Area Crop Inventory Experiment (LACIE), as described by MacDonald and Hall (1978), which has concentrated on discriminating wheat from other vegetation, estimating hectarage, and forecasting yields in the Great Plains. Coupled with this experimental effort, mathematical models have been developed that predict spectral reflectance from plant canopies as a function of solar, plant, and soil parameters. Notable among these mathematical models are the stochastic model developed by Oliver and Smith (1973) and the deterministic model of Suits (1972). This paper discusses results we obtained using the Suits Model.

Abstract: *Variables that characterize wheat canopies for the Suits Model and spectral bidirectional reflectance measurements in the 450 to 1350 nm interval were determined approximately weekly throughout the growing season for two cultivars of wheat that achieved maximum leaf area index of 5.3 and 10.8. The Suits Model plant variables were tabulated and experimental reflectance measurements were compared with the model predictions in the wavelength interval from 500 to 1150 nm at 50 nm increments for 17 measurement dates. The seasonal average coefficient of determination,* r^2*, was 0.88 between the Suits spectral bidirectional reflectance model and field-measured reflectance data. Poorest agreement was found very early and very late in the growing season, possibly due to low green plant biomass and incomplete ground cover.*

The Suits Model, a refinement of the Allen, Gayle, and Richardson Model (1970),

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is a three compartment model that uses upwelling diffuse, downwelling diffuse, and solar specular flux within the canopy as the three variables. Solar energy conservation considerations are used to derive a system of differential equations whose solution depends upon specification of plant optical characteristics and soil background reflectance. Detailed explanations of the Suits Model can be found in Suits (1972), Chance and Cantu (1975), and in Bunnik (1978). The authors have reported on properties of the Suits Model in Chance and LeMaster (1977), LeMaster and Chance (1977), and Chance and LeMaster (1978), and have verified the model using both their own field data and data collected by Kanemasu (Chance, 1977).

The purpose of this paper is to report (a) measurements of the Suits parameters for field-grown wheat, taken approximately weekly throughout the growing season; (b) a comparison of Suits Model calculations of bidirectional reflectance with experimental data taken on 17 dates; and (c) an experimental relationship between leaf biomass and leaf area index (LAI).

Data Collection Techniques and Procedures

Two cultivars of wheat *Triticum aestivum* [L.]—Penjamo, a fast maturing, sparse-tillering Mexican-type spring wheat, and Milam, a tillering, hard red winter wheat—were used in this study. Plots of about 1 ha each at the USDA, SEA Research Farm at Weslaco, Texas, were seeded at 60 kg/ha with Milam wheat and at 90 kg/ha with Penjamo wheat on 3 and 6 December 1976. Milam emerged 10 December and the Penjamo emerged on 15 December.

The following crop variables were measured on 17 dates spaced about a week apart: LAI, leaf biomass, plant biomass, hemispherical reflectance, and, whenever possible, transmittance of all canopy components (heads, stems, green leaves, and brown leaves when they occurred in the canopy), crop spectral reflectance, Suits Model variables, directional reflectance of the crop at 500 nm and 850 nm, and bare soil spectral reflectance.

Values of the LAI were determined by using the total leaf area of all leaves, both green and brown, as measured with an optical planimeter made by Hyashi Denko*. All leaves were removed from plants along 25 to 100 cm segments of two adjacent rows judged by the authors to be characteristic of the site viewed by the spectroradiometer. The leaf area index was then calculated by the ratio of the total area of all the leaves from the plants sampled to the ground area occupied by the plants. This value represents the number of layers of leaves that would be obtained by removing all the leaves from a plant and laying them on the ground occupied by the plant, e.g., ground area = 50 cm of row by 17.7 cm row spacing.

Stems and heads were also run through the optical planimeter; their areas and projected areas were used in the model calculations. Since the green heads and stems are photosynthetically active, their areas were included in calculating leaf area index.

Hemispherical reflectance and transmittance of the vegetative components of the plants (green leaves, heads, stems, and brown leaves) were determined each week by removing representative plants from the field and immediately transporting them in plastic bags over ice 10 km to the DK-2A spectrophotometer at the USDA laboratory in Weslaco, Texas. The instrument port was covered with selected vegetative component samples, and the hemispherical reflectance and transmittance were measured at 50 nm intervals from 500 to 2500 nm on a Beckman DK-2A spectrophotometer.

The reflectance values for stems, heads, and leaves remained fairly constant (±10 percent) for most of the growing season. Representative values of reflectance and transmittance are shown for Penjamo on 8 March 1977 in Table 1.

Relative bidirectional reflectance values were determined each week for both varieties of wheat. Measurements were taken from a 6m tower using a vertical look angle with an ISCO spectroradiometer equipped with a 1.8 m fiber optics probe that had a 13° field of view to half maximum. The spectral bandwidth was 15 nm in the visible and 30 nm for wavelengths greater than 700 nm. Reflectances were determined relative to a plywood panel coated with several layers of barium sulfate-based paint (Eastman Kodak White Reflectance Coating #6080). The fraction of diffuse skylight was measured each week at the time the crop reflectance was being measured. The radiance of the standard reflectance panel placed in full sunlight was measured with the field spectroradiometer. A small opaque screen was then used to block the direct sunlight from the standard panel; the irradiance of the panel under this condition was the diffuse

* Trade names and company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the mentioned product by Pan American University or the USDA.

TABLE 1. HEMISPHERICAL REFLECTANCE AND TRANSMITTANCE OF THE VEGETATIVE COMPONENTS BY 50 nm INTERVALS OVER THE WAVELENGTH RANGE 500 TO 1500 nm. BARE SOIL REFLECTANCE VALUES ARE NOT SHOWN FOR WAVELENGTHS GREATER THAN 1150 nm BECAUSE THE FIELD RADIOMETER WAS NOT SENSITIVE ENOUGH AT THESE WAVELENGTHS

Wavelength (nm)	Heads	Green leaves		Stems	Brown leaves		Soil
	ρ	ρ	τ	ρ	ρ	τ	ρ
500	0.069	0.085	0.001	0.145	0.112	0.063	0.055
550	0.113	0.129	0.029	0.242	0.177	0.147	0.074
600	0.085	0.085	0.001	0.176	0.118	0.094	0.085
650	0.042	0.062	0.001	0.090	0.072	0.021	0.085
700	0.266	0.276	0.157	0.437	0.300	0.286	0.104
750	0.498	0.445	0.314	0.616	0.396	0.385	0.109
800	0.510	0.445	0.320	0.619	0.394	0.392	0.122
850	0.510	0.444	0.325	0.615	0.389	0.396	0.122
900	0.500	0.442	0.324	0.602	0.387	0.397	0.140
950	0.456	0.437	0.323	0.553	0.386	0.397	0.136
1000	0.478	0.439	0.326	0.574	0.383	0.405	0.173
1050	0.492	0.436	0.334	0.590	0.377	0.412	0.177
1100	0.476	0.430	0.333	0.563	0.374	0.408	0.181
1150	0.370	0.407	0.314	0.464	0.362	0.406	0.170
1200	0.375	0.410	0.319	0.468	0.363	0.405	—
1250	0.374	0.405	0.324	0.467	0.356	0.412	—
1300	0.324	0.388	0.300	0.419	0.352	0.398	—
1350	0.261	0.356	0.271	0.353	0.330	0.381	—
1400	0.109	0.193	0.127	0.203	0.225	0.250	—
1450	0.074	0.169	0.090	0.172	0.199	0.226	—
1500	0.102	0.213	0.135	0.207	0.235	0.283	—

component of the skylight. The ratio of shadow to sunlight radiometer readings at a given wavelength yielded the fraction of diffuse irradiance on the crop. This fraction was used as an initial condition in the Suits model calculation of bidirectional reflectance.

Soil reflectance values used in the model calculations were obtained using a sunlit soil area within 10 metres of the crop target always within one-half hour of the time the crop reflectance was measured. Only sunlit soil was viewed for reflectance measurement. The soil area received the same cultivation and irrigation treatment as the crop. Its surface became visibly dry at about the same time as that in the crop target area. A typical soil spectral reflectance curve is shown in the lower curve in Figure 1 for a vertical view angle and a sun zenith angle of 47.2° on 22 March 1977, the 97th day after emergence.

The reflectance values for bare soil varied slightly on different dates due to changes in surface soil moisture, cultivation, and surface weathering, a finding that is consistent with Condit (1955).

The Suits Model requires several special plant variables that are experimentally determined as described in Chance and LeMaster (1978). Briefly, the values of σ_h and σ_v are the projections of leaves, stems, or heads on a horizontal or vertical plane. They are determined from the average area of the component in the layer being considered weighted by the cosine or sine of the slope angle to yield the proper projection of the area. The value for n, the number density of plant components, is found by dividing the number of leaves, stems, or heads in a layer by the volume occupied by that layer. Tables 2 and 3 summarize these parameters for

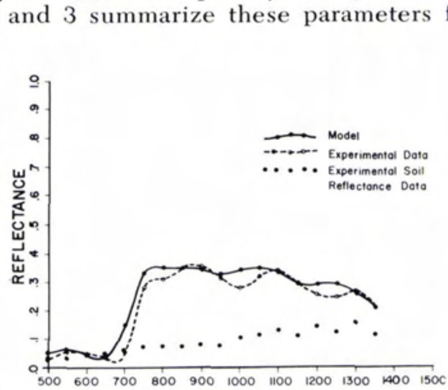

FIG. 1. The bidirectional reflectance calculated from the Suits Model and the field measurements (dashed line) with the soil (data points) included for comparison. The crop was Penjamo wheat on 22 March 1977, the 97th day after emergence. The sun zenith angle was 47.2° and the observer zenith angle 0°; the fraction of diffuse light at 550 nm was 0.19.

TABLE 2. DATES OF MEASUREMENT, PLANT AGE FROM EMERGENCE, AND SUITS MODEL PARAMETERS FOR PENJAMO WHEAT DURING THE 1976–77 GROWING SEASON

Observation date	Days after emergence	Model layers	Layer thickness ΔX cm	Dominant Plant part	n* cm^{-3}	σ_H† cm^2	σ_V§ cm^2
28 Dec.	13	I	12.1	Green leaves	3.1×10^{-3}	1.63	3.7
4 Jan.	20	I	16.5	Green leaves	3.7×10^{-3}	1.89	4.3
11 Jan.	27	I	16.5	Green leaves	5.4×10^{-3}	2.1	4.8
18 Jan.	34	I	15.0	Green leaves	7.12×10^{-3}	4.0	4.6
25 Jan.	41	I	20.0	Green leaves	1.01×10^{-2}	5.28	6.0
12 Feb.	59	I	20.0	Green leaves	1.16×10^{-2}	10.9	10.6
22 Feb.	69	I	55.0	Green leaves	4.75×10^{-3}	9.76	11.8
1 Mar.	76	I	62.0	Green leaves	2.98×10^{-3}	14.29	17.3
				Stems	7.29×10^{-4}	0	22.7
8 Mar.	83	I	9.0	Heads	1.56×10^{-2}	3.0	10.5
		II	42.0	Green leaves	2.11×10^{-3}	11.47	11.6
				Stems	5.84×10^{-4}	0	18.0
		III	15.0	Brown leaves	1.12×10^{-2}	4.12	1.5
				Stems	2.33×10^{-3}	0	4.5
15 Mar.	90	I	10.0	Heads	3.39×10^{-3}	6.33	14.8
		II	60.0	Green-brown leaves	1.73×10^{-3}	13.55	11.1
				Stems	7.53×10^{-4}	0	20.5
		III	13.0	Brown leaves	7.3×10^{-3}	7.31	0
				Stems	3.48×10^{-3}	0	3.4
22 Mar.	97	I	9.0	Heads	5.7×10^{-3}	2.98	11.6
		II	30.0	Green-brown leaves	2.03×10^{-3}	12.14	11.3
				Stems	1.73×10^{-3}	0	10.2
		III	54.0	Brown leaves	4.54×10^{-3}	6.74	5.9
				Stems	9.63×10^{-4}	0	18.5
31 Mar.	106	I	9.0	Heads	5.78×10^{-3}	2.98	11.6
		II	30.0	Green-brown leaves	2.03×10^{-3}	12.14	11.3
				Stems	1.73×10^{-3}	0	10.3
		III	54.0	Brown leaves	4.54×10^{-3}	6.74	5.9
				Stems	9.63×10^{-4}	0	18.5
5 Apr.	111	I	14.0	Heads	4.12×10^{-3}	3.29	12.9
		II	79.0	Brown leaves	3.08×10^{-3}	6.12	6.8
				Stems	7.29×10^{-4}	0	27.9
14 Apr.	118	I	9.0	Heads	4.46×10^{-3}	3.29	12.9
		II	85.0	Brown leaves	3.1×10^{-3}	4.49	5.0
				Stems	4.72×10^{-4}	0	27.9

* Average number of components per cm^3 in layer found by counting the leaves, stems, or heads and dividing by the volume bounded by the layer thickness, the center-to-center row spacing, and the length of row sampled.
† Measured average horizontal surface area of the component plant parts projected on a horizontal plane within the respective layers.
§ Measured average vertical surface area of the component plant parts projected on a vertical plane within the respective layers.

Penjamo and Milam, respectively, for 17 dates during the growing season. They are used along with the reflectance and transmittance of the respective vegetative components (heads, leaves, stems, etc.) of Table 1, the soil reflectance, the fraction of diffuse irradiance, and the sun and observer zenith angles to implement the Suits Model calculations of the canopy reflectance. Tables 2 and 3 specify the vegetation components found in each respective layer of the canopy on each date. For example, a single layer of green leaves predominated in the Penjamo wheat canopy until 1 March when the stems became visible to the eye; by the time the plants headed (8 March), three distinctive layers were apparent in the canopy: heads, green leaves, and a layer of senescent brown leaves of Tables 2 and 3. The numbers showing vertical thickness of each layer, in column four, are negative in applying the Suits Model due to the choice of the coordinate system. More than one type of vegetative component can exist within a given layer, for example, green leaves and stems in layer II (8 March 1977).

RESULTS

CANOPY COMPONENT MEASUREMENTS

A significant finding from the large amount of data on single green leaf trans-

TABLE 3. DATES OF MEASUREMENT, PLANT AGE FROM EMERGENCE, AND SUITS MODEL PARAMETERS FOR MILAM WHEAT DURING 1976–77 GROWING SEASON

Observation date	Days after emergence	Model layers	Layer thickness ΔX cm	Dominant plant part	n* cm^{-3}	σ_H† cm^2	σ_V§ cm^2
20 Dec.	10	I	10.2	Green leaves	3.29×10^{-3}	4.86	4.7
28 Dec.	18	I	16.5	Green leaves	1.13×10^{-3}	2.59	2.5
4 Jan.	25	I	14.5	Green leaves	5.32×10^{-3}	3.81	3.7
11 Jan.	32	I	14.5	Green leaves	1.22×10^{-3}	3.29	1.9
18 Jan.	39	I	13.0	Green leaves	1.16×10^{-2}	4.30	2.5
25 Jan.	46	I	11.0	Green leaves	2.05×10^{-2}	3.69	3.5
12 Feb.	64	I	22.0	Green leaves	2.13×10^{-2}	7.38	7.1
22 Feb.	74	I	33.0	Green leaves	1.11×10^{-2}	9.19	9.0
1 Mar.	81	I	42.0	Green leaves	7.72×10^{-3}	14.7	14.4
				Stems	2.9×10^{-3}	0	8.7
8 Mar.	88	I	32.0	Green leaves	1.23×10^{-3}	11.18	15.3
				Stems	4.38×10^{-3}	0	7.7
		II	10.0	Brown leaves	1.74×10^{-2}	14.32	5.2
				Stems	1.4×10^{-2}	0	2.4
15 Mar.	95	I	57.0	Green leaves	5.53×10^{-3}	12.88	17.6
				Stems	1.63×10^{-3}	0	15.6
		II	10.0	Brown leaves	4.36×10^{-2}	5.98	2.1
				Stems	7.04×10^{-3}	0	2.7
22 Mar.	102	I	50.0	Green leaves	7.05×10^{-3}	10.08	18.3
				Stems	2.12×10^{-3}	0	15.2
		II	17.0	Brown leaves	2.05×10^{-2}	8.30	0
				Stems	6.25×10^{-3}	0	5.1
31 Mar.	111	I	69.0	Green leaves	3.93×10^{-3}	10.76	18.3
				Stems	1.18×10^{-3}	4.6	29.0
		II	28.0	Brown leaves	1.52×10^{-2}	9.2	7.9
				Stems	2.21×10^{-3}	1.87	11.7
5 Apr.	116	I	38.0	Heads	1.87×10^{-3}	1.0	9.2
		II	42.0	Green leaves	5.3×10^{-3}	6.34	10.8
				Stems	1.91×10^{-3}	0	23.1
		III	30.0	Brown leaves	1.65×10^{-2}	5.02	4.3
				Stems	2.67×10^{-3}	0	16.5
14 Apr.	125	I	38.0	Heads	1.38×10^{-3}	1.0	6.4
		II	42.0	Green leaves	3.0×10^{-3}	3.97	6.7
				Stems	7.43×10^{-4}	0	19.1
		III	30.0	Brown leaves	1.36×10^{-2}	4.36	3.7
				Stems	1.04×10^{-3}	0	13.6

* Average number of components per cm^3 in layer found by counting the leaves, stems, or heads and dividing by the volume bounded by the layer thickness, the center-to-center row spacing, and the length of row sampled.

† Measured average horizontal surface area of the component plant parts projected on a horizontal plane within the respective layers.

§ Measured average vertical surface area of the component plant parts projected on a vertical plane within the respective layers.

mittance and reflectance was that the values showed little change from three weeks after emergence until the leaves senesced, as shown in Chance and LeMaster (1978). Heads and stems showed little change in reflectance as long as they were green. The transmittance of stems and heads was so small (≤2 percent) that the values were taken to be zero for model calculations.

EXPERIMENTAL CANOPY REFLECTANCE MEASUREMENTS VS. THE SUITS MODEL CALCULATIONS

Figure 1 compares model calculations, using the parameters determined on 14 March for Penjamo wheat, and experimental crop reflectance measured on the same day. The crop had three distinct layers: heads, green leaves and stems, and brown leaves and stems. The observer angle was at zenith, and the sun zenith angle was 47.2°. The experimental reflectance curve shows small depressions around 1000 nm and 1200 nm. Minor water absorption bands, which are not reproduced by the Suits Model calculations, occur at these wavelengths. The single leaf reflectance curves show no depressions; stems and heads show clear depressions at 1000 nm and 1200 nm.

A discrepancy between the experimental data and the model calculations also occurs as the curve rises to the infrared shoulder at about 700 nm. The problem was first thought to have been due to a calibration error in the

ISCO field spectroradiometer. But a calibration of this instrument with gas discharge lamps and a comparison with simultaneous data for crop reflectance taken with the USDA field spectroradiometer (Leamer *et al.*, 1974) indicated that the ISCO was correct to ±5 nm in the vicinity of 700 nm. The Beckman DK-2A spectrophotometer (the instrument used to measure the reflectance and transmittance for plant components in the model) was then tested for accuracy in this wavelength region. A slide was made from green wheat leaves and two reflectance and transmittance determinations were made, one with the photomultiplier system used in the range from 350-700 nm and the second using the solid state detector whose sensitivity ranges from 500 to 2500 nm. In the overlapping range from 500 to 700 nm, an average 25 percent disagreement in single leaf reflectance measurements was found; at 700 nm, disagreement was 65 percent. Our reported single leaf reflectance values were all determined with the 500 to 2500 nm solid state detector, and we considered them to be in error at 700 nm. Thus, in the calculations that appear in this section, all 700 nm crop measurements and Suits Model calculations were omitted.

In Table 4, coefficients of determination are tabulated for the linear correlation of experimental data with Suits Model calculations for each of the measurement dates. The solar zenith angle at the time of each reflectance measurement is also tabulated. Using the plant parameters, the sun angle, and the fraction of diffuse skylight determined on these dates, the Suits Model calculations were made over the 500- to 1300-nm interval at 50-nm increments. The field experimental reflectance data were then regressed against the Suits Model reflectance calculations at each of 16 wavelengths except 700 nm, which was omitted, as explained above. An average coefficient of determination for the entire season was found to be 0.88 for Penjamo wheat and 0.87 for Milam wheat. On 14 April the coefficient of determination for Penjamo wheat was low; the wheat was in the golden stage and had dropped many of its dry brown leaves, which left open gaps in the canopy and caused difficulty in estimating the Suits Model plant parameters. however, the 14 April data are included in the seasonal r^2 reported.

LEAF BIOMASS AND LEAF AREA INDEX MEASUREMENTS

Figure 2 presents the seasonal progression in leaf area index (LAI) and dry weight of the leaves (leaf biomass, LBM). The LAI is a dimensionless ratio of leaf area to ground area

TABLE 4. COEFFICIENTS OF DETERMINATION (r^2) BETWEEN EXPERIMENTAL REFLECTANCE MEASUREMENTS AND SUITS MODEL PREDICTIONS FOR 17 MEASUREMENT DATES WITH THE SOLAR ZENITH ANGLE (θ_s) AND THE FRACTION OF DIFFUSE SKYLIGHT AT THE TIME OF THE EXPERIMENTAL MEASUREMENTS DURING THE 1976–77 GROWING SEASON

Observation date	Skylight Fraction 550 nm	Skylight Diffuse 850 nm	Penjamo θ_s (°)	Penjamo r^2	Milam θ_s (°)	Milam r^2
20 Dec.	1.00	1.00	—	Not emerged	52.1	0.90
28 Dec.	0.17	—	53.6	0.83	69.3	0.79
7 Jan.	0.20	0.14	64.9	0.79	68.3	0.70
18 Jan.	0.23	0.15	49.7	0.92	53.0	0.84
27 Jan.	0.13	0.14	47.0	0.93	45.7	0.94
5 Feb.	0.17	0.15	49.4	0.72	54.2	0.93
15 Feb.	0.71	—	50.9	0.97	55.8	0.98
17 Feb.	0.15	0.11	53.7	0.83	48.9	0.71
24 Feb.	0.22	0.16	37.3	0.98	37.3	0.97
8 Mar.	0.15	0.14	50.7	0.98	50.7	0.97
14 Mar.	0.20	0.20	39.2	0.96	39.2	0.86
22 Mar.	0.19	0.17	47.2	0.98	47.2	0.97
27 Mar.	0.11	0.07	40.9	0.92	40.9	0.97
5 Apr.	0.18	0.18	50.4	0.93	50.4	0.87
7 Apr.	0.15	0.17	25.6	0.91	25.6	0.87
14 Apr.	1.00	1.00	52.1	0.47	52.1	0.78
3 May	0.24	0.24	—	Harvested	40.3	0.77
Seasonal average				0.88		0.87

occupied by the plant sample; since a 25 cm long row segment was sampled and wheat rows were 17.7 cm apart, the ground area used in the ratio was 442.5 cm^2. The value of the LAI does not depend on the size of the sample area. The LBM is the mass of the same leaves used for LAI measurements after they had been air dried at 35°C for several weeks. The LBM was normalized to 1 m^2 of sample area.

The spring wheat, Penjamo, has a shorter development cycle than the winter wheat, Milam; according to Figure 3, it had headed by day 77 after emergence, whereas the winter wheat, Milam, required 110 days to reach the head stage. Both LAI and LBM reach a plateau value by the boot or head stage. During grain filling and ripening the plants senesce. Carbohydrate from the leaves is translocated to the grain and lower leaves are shed or broken off by weathering.

The data of Figure 2 show the LBM and LAI follow similar time courses. In this study, the Penjamo produced 390 heads/m^2 and the Milam, 610 heads/m^2. Each tiller that produces a head usually has five to seven leaves. Therefore, LAI determinations are time consuming and tedious.

Figure 2 displays the relation between LBM and LAI for samples taken when LAI was increasing. The data for the two cultivars has been pooled. The coefficient of determination, r^2, is 0.967** (significant at the 99% level), and the estimation equation is

$$\text{LAI} = 0.459 + 0.020\ (\text{LBM})$$

where LBM is measured in g/m^2.

The intercept of 0.459 for the LAI at zero LBM indicates experimental error in the data. A study using 253 observations of this relationship was carried out for four cultivars of winter wheat by Aase (1978). His result, expressed in the same variables as this study, was

$$\text{LAI} = 0.002854 + 0.02019\ \text{LBM}$$

with an $r^2 = 0.951$. The result we obtained for the slope was within 1 percent of the value reported by Aase (1978) and indicates that the relationship is independent of cultivar.

Discussion and Conclusions

The Suits canopy reflectance model was tested extensively throughout the growing season for two cultivars of field-grown wheat that experienced a variety of environmental growing conditions. The LAI varied from 0 to 10.8 between emergence and full canopy development. Canopy reflectance was measured under sky conditions that varied from cloudless (predominantly specular light) to complete overcast (predominantly diffuse illumination). The range of test conditions was enough to identify significant model weaknesses. Agreement between the Suits spectral reflectance model and field reflectance data was good—the seasonal average coefficient of determination of 0.88 for a wide variety of field, atmospheric, and plant conditions. Generally, agreement was worst early and late in the growing season where much bare soil was visible and row structure became apparent. The assumptions of the Suits Model that require a continuous canopy are not well satisfied early and late in

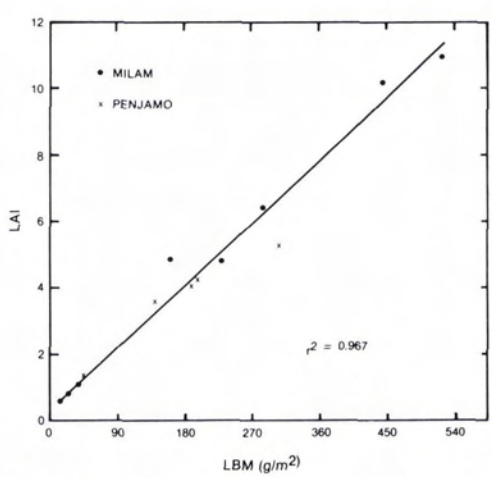

FIG. 2. Leaf biomass (LBM) measured on two varieties of wheat taken while leaf area index (LAI) was increasing.

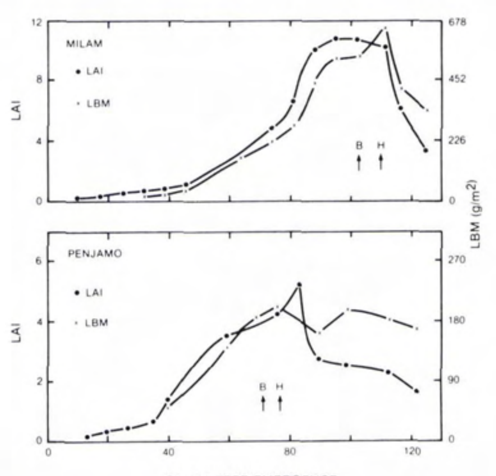

FIG. 3. Leaf area index (LAI) and leaf biomass (LBM) versus days after emergence. The B and H arrows indicate booting and heading.

the season, which accounts for the lower r^2 values during those periods.

The plant parameters listed in Table 3 have been used by Chance (1977) to predict wheat canopy bidirectional reflectance for 'Scout' wheat grown in Kansas with excellent agreement with measured reflectance. The plant parameters were chosen by using the date that matched the LAI and growth stage of the Kansas wheat. This demonstrates that the Suits parameters listed in this report can be used to calculate the bidirectional reflectance of other wheat cultivars. However, further experimental work is necessary to verify that the Suits Model can adequately model all varieties of wheat from the tables given here.

Good agreement between the LAI versus LBM measurements found here and the extensive measurements of Aase (1978) on winter wheats leads to the conclusion that LAI can be determined from dry leaf biomass, a much less time-consuming procedure.

Use can be made of the extensive soil reflectance tables of Condit (1955) if one desires to use the Suits Model to study effects of changing the soil background on a given crop.

In summary, the seasonal comparison of field bidirectional reflectance of wheat gives good agreement with the Suits deterministic model calculations, based on a seasonal r^2 of 0.88. Limitations of the Model are encountered when ground cover is incomplete, as indicated by low r^2 values early and late in the growing season.

This Model allows researchers in the field of remote sensing to establish cause and effect relations for many of the scene variables encountered: scene skylight conditions, soil reflectance, plant leaf area, leaf slope, canopy layer structure, sun angle, and observer angle. Plant photosynthesis and yield studies can utilize this Model because of its capacity to predict the energy absorption at any level in a canopy.

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