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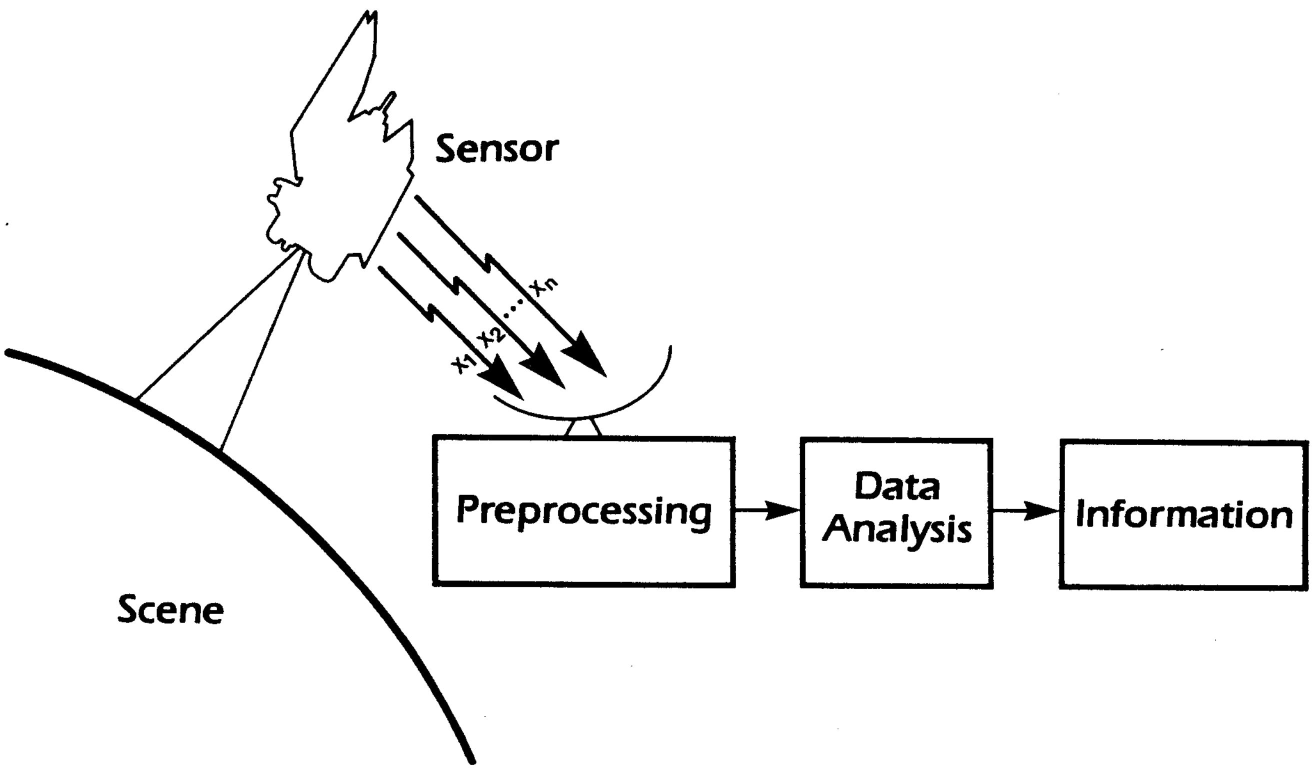

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SPECTRAL ESTIMATES OF AGRONOMIC CHARACTERISTICS OF CROPS

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ABSTRACT

If agronomic variables related to vigor and yield of crops could be reliably estimated from multispectral data, then crop growth and yield models could be implemented for large areas. The objectives of these experiments were to determine relationships of key agronomic characteristics and spectral properties of crops and to integrate spectral and meteorological data for forecasting crop yields. Reflectance data of corn, wheat, and soybeans were acquired with radiometers that simulate Landsat MSS and TM sensors. The spectral indices, greenness, and normalized difference were highly correlated with leaf area index (LAI) and absorbed photosynthetically active radiation (APAR). Grain yields were more highly related to APAR cumulated during the growing season than to maximum LAI or LAI duration. A model which simulated the daily effects of weather and APAR on growth accounted for 85% of the variation in corn yields. The concept of estimating agronomic characteristics using spectral data represents a viable approach for merging spectral and meteorological data for crop forecasting models.

I. INTRODUCTION

Remote sensing from aerospace platforms can provide information about crops and soils which could be useful for forecasting crop production. The feasibility of utilizing multispectral data from satellites to identify and measure crop area has been clearly demonstrated (MacDonald and Hall, 1980). However, relatively little research has been conducted to develop methods of incorporating multispectral data into models that provide information about crop condition and yield. If this spectrally-derived information can be combined with models that depict limitations imposed on crop yields by weather and climate, crop production over large regions could be estimated more accurately than with current systems.

Solar radiation is the source of energy for photosynthesis, the initial process that green plants use to convert carbon dioxide and water into simple sugars. Other plant processes convert these initial products of photosynthesis into dry matter including carbohydrates, proteins, and oils. Solar radiation is available as an energy source for plants only when it interacts with leaves. In a healthy crop adequately supplied with water, the production of dry matter is proportional to the solar radiation intercepted by the canopy. Thus, important components of growth and yield are the amount and duration of n plant leaf area available for photosynthesis. When water becomes limiting, stomata close, plant temperatures rise, and yields are reduced.

The interaction of solar radiation with a crop is a function of the quantity of vegetation, the geometric configuration of the canopy, and solar illumination angles (Norman, 1980). The quantity of vegetation may be described as leaf area index (LAI), percent soil cover, or phytomass. The geometry of the canopy refers to the distribution and orientation of the components of the canopy (i.e., leaves and stems). Solar zenith angle and solar azimuth angle relative to row direction are significant factors affecting radiation interception in crops. Accurate measurements of the quantity and configuration of crops are tedious and time-consuming because of the spatial variability inherent in crops (Daughtry and Hollinger, 1984). Thus direct measurements of crops are possible only for small research plots. If the proportion of energy available for crop growth could be estimated reliably using multispectral satellite data, the capability to estimate crop production for large regions should be improved significantly.

In practice, although solar radiation is essential for photosynthesis, it is only one of several factors interacting to influence crop yields. Other factors essential to crop growth and yield are water, temperature, nutrients, and carbon dioxide. Any serious and comprehensive effort to estimate crop yields also must assess the impact of these other factors.

The development of satellites with earth-observing sensors (e.g., Landsat MSS and TM) has made available enormous quantities of data containing information about the condition of the earth's surface. Conceptual models of how these remotely sensed data could be used to obtain estimates of intercepted radiation by plant canopies have been proposed (Daughtry et al., 1983; Wiegand et al., 1979). Seasonal changes of spectral variables of corn and wheat canopies followed that of light absorption (Daughtry et al., 1983; Hatfield et al., 1984). Absorption of photosynthetically active radiation (PAR) can be estimated reliably using spectral reflectance data of plant canopies (Asrar et al., 1984a, b; Hatfield et al., 1984).

Changes in LAI, phytomass, and stage of development are manifested in the reflectances of crop canopies. Soil color and moisture are important factors influencing the reflectance in single wavelength bands; however, the near infrared/red reflectance ratio and the greenness transformation were less sensitive than single bands to changes in soil background (Kollenkark et al., 1982). LAI can be estimated by the near infrared/red ratio (Bunnik, 1978; Walburg et al., 1982), by the greenness transformation (Kollenkark et al., 1982; Daughtry et al., 1983), by the normalized difference (Asrar et al., 1984a; Gardner et al., 1984), and by logarithms of two band ratios (Gardner et al., 1984).

The transmission of PAR in canopies may be used to estimate LAI indirectly. Fuchs et al.(1983) obtained good agreement between the measured and estimated LAI values for several cultivars of spring and winter wheat grown under different conditions and management practices.

Spectral reflectance, PAR absorption, and LAI are interrelated. Our objectives are (1) to determine the relationships of canopy characteristics to the reflectance factor of crops, and (2) to integrate spectral and meteorological data for estimating crop yields.

II. METHODS AND MATERIALS

A. CORN

Two experiments were conducted at Purdue University's Agronomy Farm located near West Lafayette, IN (40° 28' N, 87° 00' W). In the first experiment, corn (Zea mays L.), hybrid 'Adler 30X', was planted in north-south rows with a 76 cm spacing between rows on two dates (14 May and 24 June 1982) at two densities (50,000 and 100,000 plants/ha). The soil was a Typic Argiaquoll, a dark (10 YR 4/1) silt loam (Chalmers). In the second experiment, the same corn hybrid was planted on three planting dates (14 May, 9 and 24 June 1982) at four densities (25, 50, 75, and 100 thousand plants/ha).

Additional experiments were conducted at the University of Nebraska's Sandhills Agricultural Laboratory located near Tryon, NE (41° 37' N, 100° 50' W). Two corn hybrids, Pioneer 3901 and B73xMo17, were planted in 76 cm wide rows at 76,000 plants/ha on 17 May 1982. The soil was a fine sand Typic Ustipsament (Valentine). A gradient irrigation system provided 100, 66, 33, and 0% of the maximum water requirements of the crop.

Maximum and miniumum air temperatures, incoming solar radiation, precipitation, evaporation, and wind run were recorded daily. Agronomic variables which were measured weekly included leaf area index, stage of development, fresh and dry phytomass, plant height, and percent soil cover. Crop phytomass was measured by harvesting five plants from each plot. Each sample was weighed immediately (fresh phytomass), separated into green leaves, stalk (including leaf sheath), and ears, and dried at 82°C. Leaf area (one side of leaf) was measured with a LI-COR LI-3100 area meter from a subsample of two plants per plot. Total leaf area for the five plants was computed using the dry weight of leaves and the leaf area to weight ratio. Leaf area index was computed as the ratio of leaf area per soil area. After physiological maturity, grain was harvested, adjusted for 15.5% moisture, and reported as Mg/ha.

Photosynthetic photon flux density (PPFD) was measured under clear skies with a line quantum sensor (LI-COR 191SB). The sensor is cosine corrected and responds to radiation in the 400 to 700 nm wavelength region. Incident PAR (PAR), transmitted PAR (TPAR), and PAR_o reflected from the canopy $RPAR_{CS}$) and PAR reflected from the soil ($RPAR_S$) were measured under clear sky conditions within 0.5 h of solar noon on selected dates throughout the growing season. The proportions of absorbed PAR were calculated using Eq. 1:

$$APAR' = [(PAR_o + RPAR_s) - (TPAR + RPAR_{cs})]/PAR_o \quad (1)$$

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

Reflectance factor data were transformed to emphasize green vegetation and to minimize variation due soil color and soil moisture. One transformation is normalized difference (ND):

$$ND = (RF_i - RF_r)/(RF_i + RF_r)$$

where, RF_i and RF_r are the reflectance factors in the near infrared (800-1100 nm) and red (600-700 nm) regions of electromagnetic spectrum for Landsat MSS radiometers, respectively. For Landsat TM radiometers RF_i and RF_r are reflectance factors in 760-900 nm and 630-690 nm bands, respectively. Another important transformation for vegetation is called greenness index. Coefficients for calculating greenness index (GI) from reflectance factor data in Landsat MSS bands (Rice et al., 1980) are given in Table 1. For reflectance factor data in Landsat TM bands, a new greenness index (GI_{TM}) was developed (Table 1) using the procedures of Miller et al.(1984).

Table 1. Coefficients for greenness index for reflectance factor data of Landsat MSS and TM radiometers.

Landsat MSS			Landsat TM		
Band	Wave-length	Coefficient*	Band	Wave-length	Coefficient
	nm			nm	
MSS4	500-600	-0.4984	TM1	450-520	-0.0283
MSS5	600-700	-0.6125	TM2	520-600	-0.0330
MSS6	700-800	0.1729	TM3	630-690	-0.0807
MSS7	800-1100	0.5854	TM4	760-900	0.9411
			-	1150-1300	-
			TM5	1550-1750	-0.2000
			TM7	2080-2350	-0.2568
			TM6	10400-12500	

* From Rice et al., 1980

B. WHEAT

Spring wheat (Triticum aestivum Desf., cv. Produra) was planted in north-south rows in an Avondale loam (fine, loamy, mixed (calcareous)), hyperthermic Anthropic Torrifluvent) at the U.S. Water Conservation Laboratory, Phoenix, AZ, during the 1978-79 and 1979-80 growing seasons. The treatments were five planting dates and four irrigation rates within a planting date. Development of plants in the last planting date were retarded because of sowing into a dry soil with increasing daylengths. This resulted in a poor stand and low phytomass values. Six plants were randomly selected from each treatment and their brown and green leaf areas were determined. The measured green leaf area index for each treatment was used to compute the absorbed photosynthetically active radiation (PAR) for each date using a relationship for wheat described by Hipps et al.(1983).

Canopy reflectance was measured over each plot using a Landsat band radiometer (Exotech 100A) under clear sky conditions with the sun at a zenith angle of 57°. The radiometer was held at arm's length at 1.5 m above the soil surface. Canopy reflectance factors were determined from a ratio of the canopy and barium sulfate panel reflectances (Biehl and Robinson, 1983).

In a second experiment (Triticum aestivum L., cv. TAM 105) planted in north-south rows during the 1981-82 growing season at Kansas State University's Evapotranspiration Laboratory Research

Site near Manhattan, KS. An Exotech 100A radiometer mounted on a truck boom was used for measurements of plant canopy reflectance. Green LAI was determined by harvesting three 0.3 m sections of rows of each plot.

III. RESULTS AND DISCUSSION

A. RELATION OF CANOPY REFLECTANCE TO AGRONOMY CHARACTERISTICS

Trajectories of ND, greenness, PAR, and LAI throughout the growing season are shown in Figure 1 for wheat. Trajectories of these variables were similar for corn. Greenness and LAI appear closely related. Although LAI increased above 4, greenness changed very little until LAI declined at the end of the season. ND and absorbed PAR also appear very closely related throughout the season (Fig. 1).

The relationships of other canopy characteristics and spectral variables are nonlinear over the ranges of values observed in these experiments (Kollenkark et al., 1982; Tucker, 1979; Walburg et al., 1982). Quadratic regression equations adequately described the canopy characteristics as functions of spectral transformations. Changes in LAI, soil cover, and absorbed PAR were more highly related to the spectral variables than either fresh or dry photomass (Table 2). Greenness and ND transformation had stronger relationships to these variables than Red, NIR, or NIR/Red (Table 2).

Why are the R^2 for LAI, percent soil cover, and absorbed PAR as functions of ND and greenness much higher than those for fresh and dry phytomass (Table 2)? Reflectance is a function of the areas of the reflecting elements of the canopy projected in the direction of the sensor. Leaves constitute a majority of the areas of reflectors in most growing crop canopies when viewed vertically from above. Stems and other nonleaf components (e.g., heads, tassels, ears) are a small portion of the reflecting area. LAI, percent soil cover, and absorbed PAR are functions of the area of green leaves in the canopy. In some crops (i.e., corn and wheat) leaf area, leaf phytomass, and greenness all reach maximum values as the plants begin their reproductive development. During this reproductive phase, plants accumulate phytomass primarily in grain which may contribute only a small portion of the

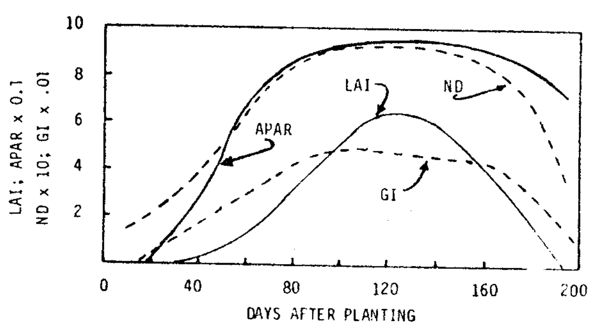

Figure 1. Trajectories of absorbed PAR (APAR), leaf area index (LAI), normalized difference (ND), and greenness index (GI) for well-watered Produra wheat throughout its growing season.

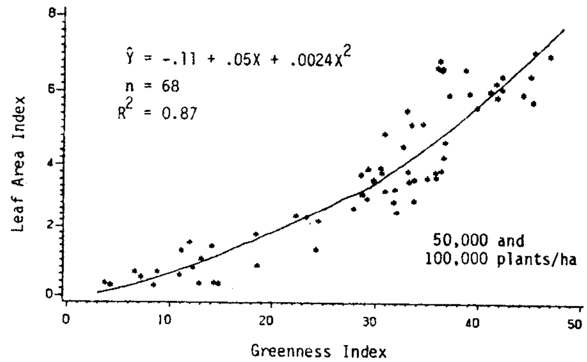

Figure 2. Leaf area index of corn in 1982 as a function of greenness index.

Table 2. Coefficients of determination (R^2) for agronomic variables of corn as quadratic functions of NIR/Red ratio, normalized difference (ND), and greeness index (GI_{TM}) for Landsat TM bands.

Agronomic Variable	NIR/ Red	ND	GI	Range of Data
	------R^2------			
LAI	0.72	0.71	0.87	0-7.2
Soil Cover	0.84	0.81	0.81	0-99%
Fresh Phyto*	0.51	0.49	0.63	0-11.0 Kg/m^2
Dry Phyto	0.26	0.20	0.31	0- 3.0 Kg/m^2
Absorbed PAR	0.89	0.89	0.94	0-99%

* Phyto = total above-ground phytomass.

total plant area viewed by the sensor. Therefore, after maximum leaf area has developed, continued accumulations of phytomass probably are not spectrally detectable.

The response of greenness to LAI appears asymptotic for LAI greater than approximately 5 (Fig. 2). The response ND to LAI is definitely asymptotic for wheat (Fig. 3) and corn (not shown). Very little change in ND is evident after LAI exceeds 3.0. This is consistent with infinite reflectance of single leaves where visible reflectance was minimized with two layers of leaves and near infrared reflectance was maximized with 6 to 8 layers (Gausman et al., 1968).

Absorption of PAR by crop canopies is dependent on the stage of development or age of the plant (Fig. 1). Initially as LAI increased, absorption of PAR increased rapidly (Figs. 4 and 5). Absorption increases slowly as LAI continues to increase. The relationship between LAI and interception of radiation may be described in terms of Beer's Law (Norman, 1980; Fuchs et al., 1983; Asrar et al., 1984b).

As green LAI decreased during senescence, absorption of PAR decreased slowly (Figs. 4 and 5). Even at maturity, when no green leaves were present, more than 60% of PAR was absorbed by nongreen leaves, stems, and other plant parts.

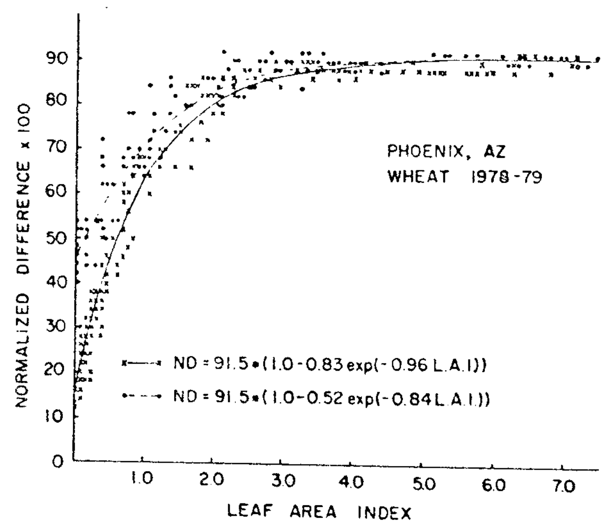

Figure 3. Relation between normalized differences (ND) and leaf area index for the growth (i.e., planting to heading) and senescent (i.e.,heading to maturity) periods of wheat.

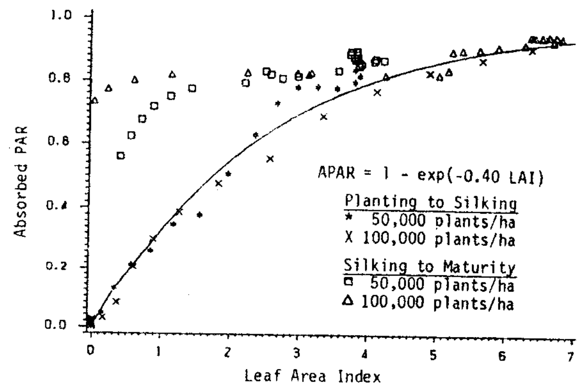

Figure 4. Relation between absorbed PAR and leaf area index for growth (planting to silking) and senescent (silking to maturity) periods of corn.

The relationships of absorbed PAR to greenness (Fig 6) and ND (not shown) are biphasic. Two equations were required to describe APAR as a function of increasing and decreasing greenness (or ND), respectively. The hysteresis in Figure 6 is due to the spectral reflectance and PAR absorption of senesced vegetation. High R^2 and low standard deviations indicate strong correlations of PAR absorption to these two spectral variables.

B. RELATION OF SPECTRAL VARIABLES TO YIELD

The seasonal duration of leaf area is a more important indicator of grain yields than maximum LAI produced (Daughtry et al., 1983; Blad et al.,1983). Correlations of grain yields with spectral or agronomic data acquired on a single date during the season may be spurious and must be used with caution. Leaf area duration (Σ LAI) accounted for only 55% of the variation in grain yields of corn in 1982. LAI of a crop represents only the amount of photosynthetic tissue present in the canopy but does not account for productivity. Canopies with low seasonal values of LAI absorbed the least PAR and produced the lowest yields. When the daily photon flux density of PAR absorbed (Σ APAR) by the crop was estimated using greenness (Fig. 6) and accumulated over the season, APAR was associated with 81% of the variation in corn yields (Fig. 7). It appears that the energy absorbed by a crop is more indicative of yields than LAI. High correlations of yields and various cumulated spectral variables have been reported for wheat (Pinter et al., 1981), sugar beets

(Steven et al., 1983), and corn (Daughtry et al., 1983; Walburg et al., 1982; Gardner and Blad, 1984).

Crop response to PAR is confounded with the effects of temperature and moisture on plant growth and yields. Thus the applicability of models based solely on spectral data may be limited.

To account for the daily effects of weather on corn growth, Coelho and Dale (1980) proposed the Energy-Crop Growth (ECG) model, which combines the concept of intercepted solar radiation with a mois-

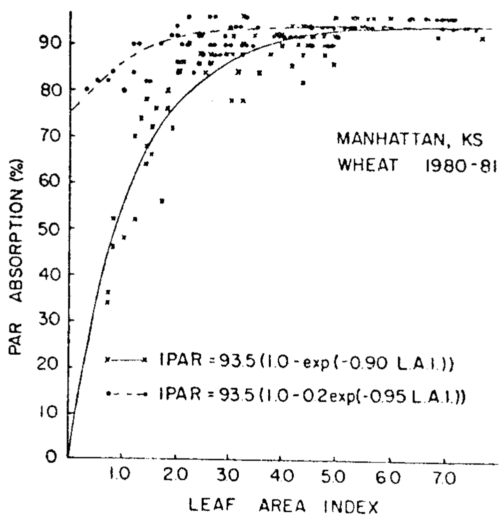

Figure 5. Relation between absorbed PAR and leaf area index for growth (planting to heading) and senescent (heading to maturity) periods of wheat.

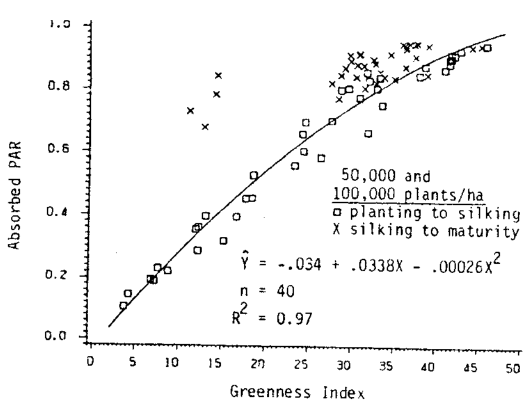

Figure 6. Relation between absorbed PAR and greenness index for growth (planting to silking) and senescent (silking to maturity) periods of corn.

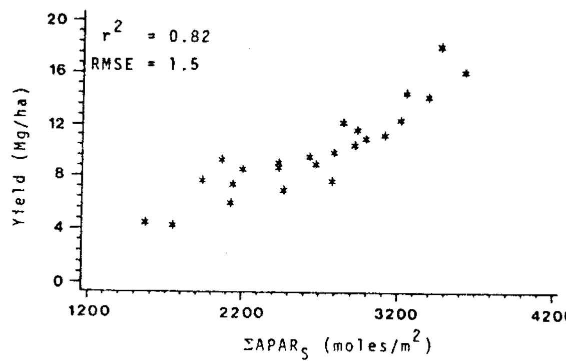

Figure 7. Grain yields of corn in 1982 as a function of absorbed photosynthetic photon flux density (APAR). APAR is the cumulated product of daily APAR, estimated by greenness index, and daily incident PAR.

ture stress term and a temperature function. The modified form of the ECG model used was:

$$ECG = \sum_{i=planted}^{mature} (PAR_i/PAR_{max})(APAR_i)(WF_i)(FT_i)$$

where, PAR_i is the daily incident (moles/m^2) and PAR_{max} is the theoretical maximum amount of daily PAR (71.8 moles/m^2) for the location of this study. APAR is the proportion of incident PAR that is absorbed by the canopy; WF is the daily ratio of actual to potential evapotranspiration (ET/PET) (Stuff and Dale, 1978); and FT is a daily temperature function (Coelho and Dale, 1980).

The sum of the daily values of ECG is associated with 85% of the variation in corn yields (Fig. 8). Although the combinations of planting dates in 1982 represented a wide range of temperatures, radiation, and daylength regimes, significant water stress was not evident among the treatments. In west central Indiana where these experiments were conducted record corn yields were reported in 1982 (USDA, 1982). In other years (e.g., 1983) when moisture and/or temperature limited crop production, the ECG model should be superior to models using only spectral or only meteorological data for predicting crop yields. We are currently assembling and analyzing data to evaluate the effects of these stresses on crop yields.

The concept of combining spectral estimates of canopy characteristics with meteorological models should permit implementation of crop models for large areas.

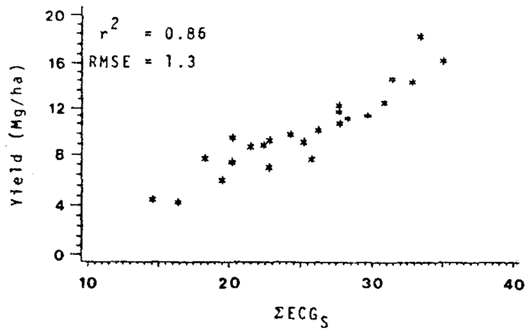

Figure 8. Grain yields of corn in 1982 as a function of the energy-crop growth (ECG) model. The ECG model combines the concept of absorbed PAR with moisture stress and temperature functions to describe crop growth and yield.

A crop production forecasting system using meteorological and spectral data could exploit the frequent temporal sampling typical of weather data with the high spatial resolution typical of earth observing satellites (Daughtry et al., 1983; Wiegand et al., 1979). Multispectral data from satellites could form the basis for estimating crop production over regions where ground observations are difficult or too costly to obtain directly.

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