Spectral Estimates of Solar Radiation Intercepted by Corn Canopies[1]

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ABSTRACT

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 areas. 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. 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. 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.

Additional index words: Remote sensing, Reflectance, Grain yield, Crop models, *Zea mays* L.

In recent years the world's food situation has emphasized the need for timely information on worldwide crop production. Remote sensing from aerospace platforms can provide information about crops and soils that could be useful to crop production forecasting systems. The feasibility of utilizing multispectral data from satellites to identify and measure crop area has been demonstrated (14), however, relatively little research has been conducted on developing the capability of using multispectral data to provide information about crop condition and yield. If this spectrally derived information can be combined effectively with crop models which depict limitations imposed on crop yields by weather and climate, then better information about crop yield and production can be gained.

Solar radiation is the source of energy for photosynthesis, the initial process that green plants use to convert CO_2 and water into simple sugars. Other plant processes convert these initial products of photosynthesis into dry matter (DM) 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 plant surface available for photosynthesis (2,4).

In theory, the production of DM over time period t, beginning at emergence and ending at maturity, can be related to the proportion (P) of the incident solar radiation (SR) intercepted by the crop using the following

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equation from Steven (19):

$$DM = \int_{emerge}^{mature} E\ P\ SR\ dt\ . \qquad [1]$$

E is the efficiency of conversion of solar energy into DM and typically ranges from 1 to 3 g/MJ (15). This equation can be used to predict DM production if P is known. Current methods to measure the radiation intercepted by crops are laborious and limit use of such crop models to small research plots. If the proportion of energy available for crop growth could be estimated reliably using multispectral satellite data, then 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 CO_2. Any serious and comprehensive effort to estimate crop yields must assess the impact of these other factors.

Our overall objective is to develop methods for combining spectral and meteorological data in crop yield models which are capable of providing accurate estimates of crop condition and yields throughout the growing season. This paper presents our initial tests of these concepts using spectral and agronomic data acquired in controlled experiments. Future research will extend those methods that best estimate yields at agricultural experiment stations to large areas using spectral data acquired by satellites.

MATERIALS AND METHODS

Design of Experiment

Spectral and agronomic data used in these analyses were acquired at the Purdue University Agronomy Farm in 1979 and 1980. A full season corn (*Zea mays* L.) hybrid, Beck 65X, was grown on two soil types. When dry, the Chalmers silt loam (fine-loamy, mixed, mesic Typic Argiaquoll) had a dark gray (10YR 4/1) surface while the Toronto silt loam (fine-silty, mixed, mesic Udollic Ochraqualf) had a light gray (10YR 6/1) surface. These two soils were spectrally distinct in both visible and near infrared reflectance factor (11).

Prior to planting 200, 50, and 95 kg/ha of N, P, and K, respectively, were applied uniformly to both soils to minimize the risk that corn growth might be limited by nutrient availability. Daily meteorological data were recorded at the cooperative National Weather Service station (West Lafayette 6NW) which was within 200 m of the fields. Incoming solar radiation was measured with an Eppley Precision Spectral Pyranometer and recorded as total MJ m^{-2} day^{-1} (1MJ = 2.387 $\times$ 10^{-11} Langley). Daily maximum and minimum air temperatures were measured with liquid-in-glass thermometers in a standard Cotton Region shelter. Soil moisture in the top 105 cm (depth of drainage tiles) was estimated on a daily basis using a soil moisture balance model (20). Inputs to the soil moisture balance model include initial moisture content, water holding capacity, and wilting point moisture content of each soil type plus daily measurements of maximum and minimum air temperatures, precipitation, and evaporation from a standard class A pan.

Within each soil type two completely randomized blocks with three plant densities (25,000, 50,000, and 75,000 plants/ha) were planted in 76 cm wide north-south rows on 2, 16, and 30 May 1979 and 7, and 22 May, and 11 June 1980. Additional plots of the 50,000 plants/ha treatments were planted on 16 and 29 May, 18 June, and 3 July 1980. These treatments represented a wide range of planting dates and plant populations expected in corn fields in Indiana.

Canopy Characterization

Agronomic variables measured weekly included: plant height, leaf area index (LAI), development stage (8), total fresh and dry biomass, stalk (including leaf sheath), ear, and green leaf blade (lamina) dry weights. Percent crop cover (defined as the percentage of soil covered by vegetation) was determined by placing a grid over a vertical photograph and counting the intersections occupied by green vegetation. Crop biomass was estimated by harvesting three plants in 1979 and four plants in 1980 from each plot. Each sample was weighed immediately, separated into its components, dried at 75 C, and reweighed. The area of a random subsample of green leaf blades from each plot was measured with an electronic area meter (LI-COR, Model LI-3000) and the green leaf area to leaf dry weight ratio was calculated. Leaf area index was calculated using this leaf area/weight ratio, the total dry weight of green leaves from all plants sampled, and the soil area represented. Grain was harvested by hand from the center four rows of each plot (11.6 m^2), dried, weighed, and corrected to 15.5% moisture. Visual assessment of the soil moisture and crop condition were made during the spectral data collection. Crop condition assessment included evaluations of lodging and hail and insect damage.

Spectral Measurements

Radiance measurements, used to determine reflectance factor (RF), were acquired with a Landsat-band radiometer (Exotech 100) throughout the growing season in each year. Robinson and Biehl (17) describe the conditions and procedures for obtaining the RF data. The Exotech 100 has a 15° field of view and acquired data in the following wavelength regions: 0.5 to 0.6, 0.6, to 0.7, 0.7 to 0.8, and 0.8 to 1.1 μm. 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.

The radiometer and a 35-mm camera were attached to a boom mounted on a pickup truck and elevated 5.2 m above the soil in 1979 and 7.6 m in 1980. After the instruments were leveled for a nadir look angle, two measurements were taken—one centered over the row and one centered between rows—in each plot to better estimate the overall canopy response (5). A color photograph which included the area viewed by the radiometer was taken vertically over each plot and used to determine percent crop cover.

Analysis

Two methods of estimating the proportion of solar radiation intercepted by corn canopies were examined. First, the proportion of intercepted radiation (SRI_L) was described as a function of measured LAI using the following equation from Linvill et al. (12):

$$SRI_L = [1 - \exp(-0.79\ LAI)]\ . \qquad [2]$$

This is an application of Bouguer's Law using LAI and an extinction coefficient of −0.79. When LAI is 0, no energy is intercepted. When LAI is 2.8, approximately 90% of the visible solar radiation is intercepted by the canopy and is potentially useful to the crop.

The second method estimates SRI_L as a function of the spectral variable greenness. This spectrally estimated proportion of radiation intercepted is called SRI_S to distinguish it from SRI_L which is estimated using measured LAI.

The following equation was developed using data from both years of this study:

$$SRI_S = -0.1613 + 0.0811\ G - 0.0015\ G^2 \qquad [3]$$

where G is the green vegetation index or "greenness" for reflectance factor data (13). Greenness was calculated as follows: Greenness = ($-0.4894\ RF_1 - 0.6125\ RF_2 + 0.1729\ RF_3 + 0.5953\ RF_4$), where RF_1 to RF_4 refer to the reflectance factor in each of four bands of the radiometer.

Table 1. Regression analyses for LAI and SRI in 1979 and 1980 (n = 811).

Variable	Estimator(s)†	R^2	F	RMSE‡	CV (%)§
LAI	G	0.74	2270.0	0.88	48.6
	G, G^2	0.76	1245.9	0.85	47.0
	G, G^2, D, P, S	0.79	605.4	0.79	43.6
SRI	G	0.86	5063.6	0.14	24.6
	G, G^2	0.90	3632.1	0.12	21.0
	G, G^2, D, P, S	0.91	1565.3	0.11	20.3

† G = greenness, G^2 = (greenness)^2, D = plant date, P = plant density, S = soil type.
‡ Root mean square error.
§ Coefficient of variation.

Solar azimuth and zenith angles, spectral properties of canopy elements, leaf area index, leaf angle distribution, leaf size and shape, and leaf movement due to wind, wilting, and phototropism influence the interception of radiation by vegetation (16). The concept of a simple exponential extinction of radiation appears to be widely applicable. Norman (16) presents a summary of extinction coefficients reported for various canopies and sun elevation angles. For corn the extinction coefficients ranged from −1.5 for low sun angles (10°) to −0.56 for high solar elevation angles (70°). The extinction coefficient used in this research is within the range of values presented by Norman for approximately 45° solar elevation. Additional research is needed to characterize and model the changes in extinction coefficient if this approach is to be used quantitatively.

SRI_S, predicted as a function of greenness (Eq. [3]), and SRI_L, predicted as a function of measured LAI (Eq. [2]), were calculated for each day that appropriate spectral and agronomic data were acquired and linearly interpolated for intermediate days throughout the growing season for each plot. Daily values of SRI_S and SRI_L were accumulated from planting to physiological maturity. Direct correlations of final grain yields with these accumulated indices were examined.

To account for variability in temperature and plant water status, the performances of spectrally estimated SRI_S and measured SRI_L were compared using the Energy Crop Growth (ECG) model (3,4) which combines the concept of intercepted solar radiation with a moisture stress term and a temperature function. The ECG model used was:

$$ECG_L = \sum_{i-\text{planted}}^{\text{mature}} (SR_i/LE)(SRI_{Li})(WF_i)(FT_i) \qquad [4]$$

where SR is the daily solar radiation in MJ m^{-2} day^{-1} and LE is the approximate latent energy of water 2.5 × 10^3 MJ m^{-3}, WF is the ratio of daily evapotranspiration to potential evapotranspiration (ET/PET) (19), and FT is a daily temperature function (3). For the spectral ECG_S model SRI_S was calculated using Eq. [3] and substituted directly for SRI_L in Eq. [4].

RESULTS AND DISCUSSION

Relation of Canopy Reflectance to LAI and SRI

The LAI and SRI for these corn canopies were described as functions of several spectral variables and transformations using regression analyses. Previous research has indicated that greenness is highly correlated to LAI and percent crop cover but relatively insensitive to soil color (11,21). In each year and for the combined data, greenness predicted SRI better (higher R^2) than LAI (Table 1).

The response of greenness to LAI appears asymptotic for LAI greater than approximately 5 (Fig. 1). This is consistent with infinite reflectance of single leaves where visible reflectance was minimized with two layers of leaves

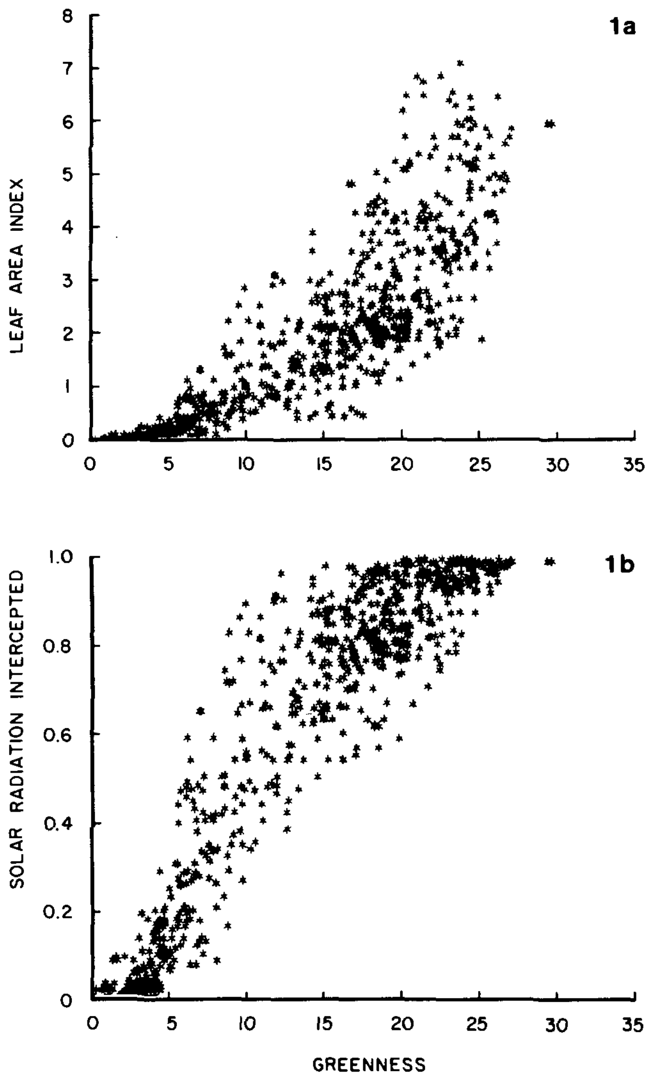

Fig. 1. Relationships of leaf area index (LAI) and solar radiation intercepted (SRI_L) to the spectral variable greenness, n = 811.

and near infrared reflectance was maximized with six to eight layers (6). Since more than 90% of the incoming solar radiation should be intercepted by corn canopies with LAI of 5.0 (4,12), the importance of accurately estimating LAI greater than 5.0 for corn canopies is diminished.

The relationships of LAI and SRI to greenness for all plots of corn in 1979 and 1980 are shown in Fig. 1. Undoubtedly planting date, plant population, and soil type contributed to the scatter about the regression line, but when included as terms in the regression models, they contributed very little additional information (Table 1). Errors in measuring LAI also account for a portion of the scatter. Nevertheless, LAI and SRI predicted as a function of greenness permit the concepts and models developed at the Purdue Agronomy Farm to be used in situations where only spectral data may be available.

Relation of Spectral Variables to Yield

Corn is a determinant crop; that is, it completes its vegetative development, producing all of its leaves, then shifts to reproductive development, producing and filling

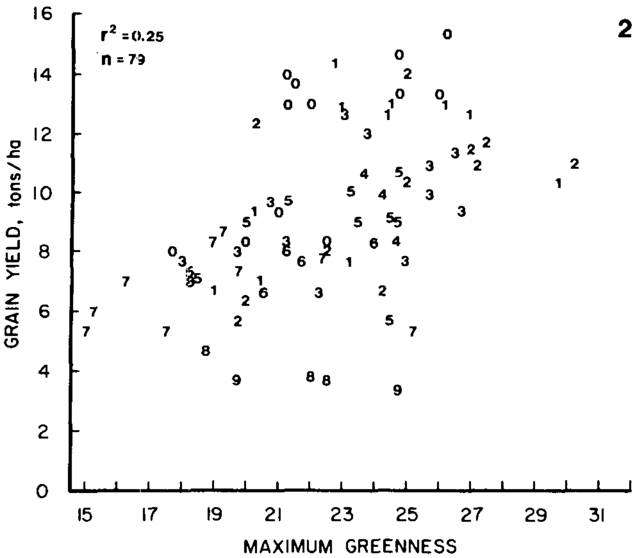

Fig. 2. Corn grain yields as a function of maximum greenness. Root mean square error is 2.6 tons/ha. The symbols are the relative planting dates for the 2 years with "0" representing the first planting date in 1979 and "9" the last planting date in 1980.

its grain. If corn grain yields are strongly related to the total amount of green leaf area present, then the maximum LAI or maximum greenness of corn should be an important predictor of grain yields. Figure 2 illustrates the error of this assumption. Grain yields are plotted as a function of maximum values of greenness which occurred near tasseling. The presence of a healthy vegetative canopy does not necessarily guarantee high levels of grain yield as corn and other determinant crops are susceptible to moisture and temperature stress during pollination and grain filling (18). Correlation of grain yield with spectral variables obtained on a single observation date may be spurious and therefore should be interpreted with caution. The poor relationship shown in Fig. 2 emphasizes the limited value of a single observation of greenness for predicting corn yields.

A more important and useful indicator of grain yields is the seasonal duration of LAI and not simply the maximum LAI achieved. Previous researchers have reached similar conclusions for other crops (4,12,19). Two variables which represent the integral of LAI over time during the growing season are accumulations of the daily values of SRI_L and SRI_S. These summed values of SRI_L and SRI_S represent the proportions of the solar radiation impinging on the corn field during the growing season that were intercepted by the corn canopy and thus were potentially available for photosynthesis (Fig. 3). Both estimates of intercepted solar radiation were associated with approximately 65% of the variation in grain yields.

One problem in crop response to solar radiation is the confounding of solar radiation, temperature, and plant moisture stress on plant growth and yields. Thus applicability of the theoretical model presented in Eq. [1] is extremely limited. Several researchers have demonstrated for various crops that the reduction in crop growth is proportional to the reduction in evapotranspiration (ET) from potential evapotranspiration (PET) (4,7,9,10). Coelho and Dale (3) combined temperature and moisture stress with an estimate of intercepted solar radiation using measured LAI in an Energy Crop Growth (ECG)

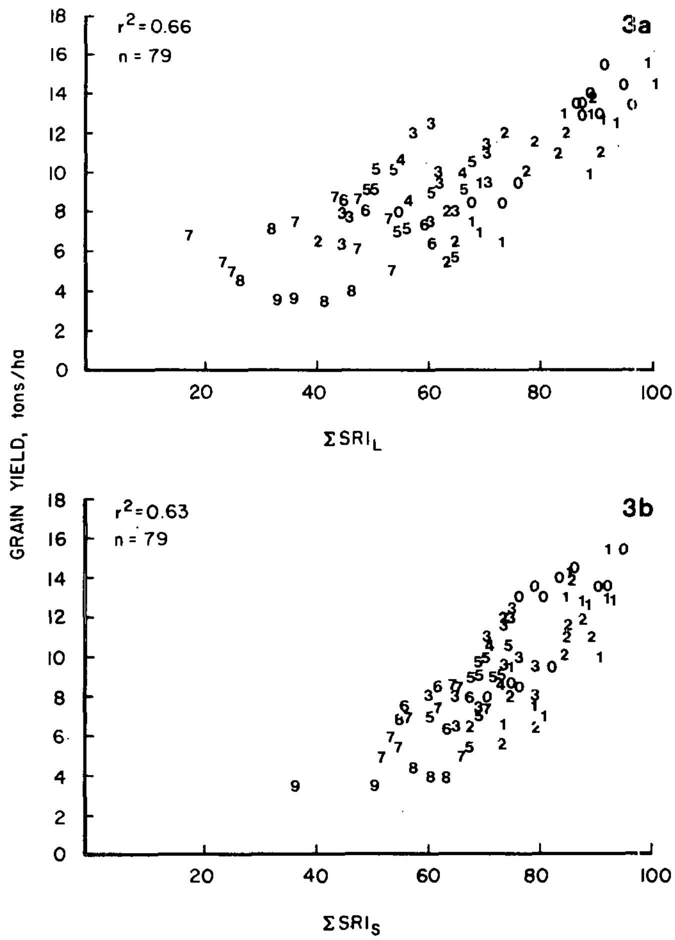

Fig. 3. Corn grain yields as a function of the accumulated proportions of solar radiation intercepted by the corn canopies. The SRI_L is estimated using measured LAI and SRI_S is estimated using spectral data. Root mean square error is 1.8 tons/ha for both SRI_L and SRI_S. The symbols are relative planting dates for the 2 years with "0" representing the first planting date in 1979 and "9" the last planting date in 1980.

model, Eq. [4]. They used this model to simulate the daily effects of weather on corn growth.

The sum of the daily values of ECG using SRI_S or SRI_L to estimate intercepted solar radiation are plotted with grain yields in Fig. 4. Both of the ECG models have slightly larger coefficients of determination (r^2) than the SRI_S and SRI_L models. Although the 10 planting date-years represented a range of temperature and daylength regimes, direct examination of daily ET/PET values revealed no significant water stress among the treatments. In this case, each of the intercepted radiation variables (SRI_L and SRI_S) were nearly as highly correlated to yields as the meteorological (ECG) models. In situations where moisture or temperature limits yield, it is postulated that either of the two ECG models should be superior to the intercepted solar radiation models for predicting corn yields.

The concept of combining spectrally derived estimates of SRI with meteorological data should enable implementation of crop growth and yield models for large areas. A spectral-meteorological system of crop forecasting could exploit the frequent temporal sampling of weather data (e.g., daily or hourly) with the high spatial resolution

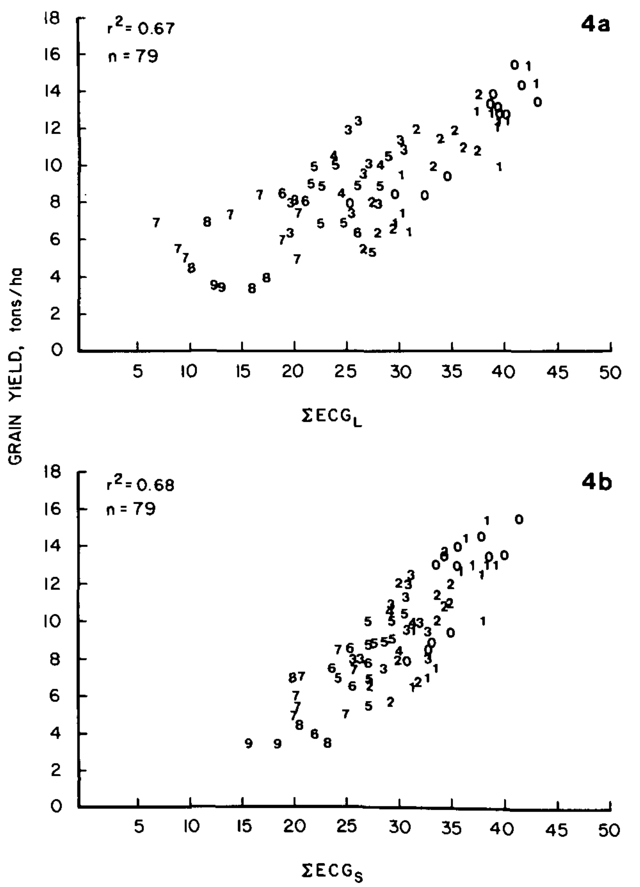

Fig. 4. Corn grain yields as a function of the accumulated ECG variable. The ECG_L is calculated using SRI_L and ECG_S with SRI_S. The units for ECG_L and ECG_S are 10^{-2} m evaporated water. Root mean square error is 1.7 tons/ha for both ECG_L and ECG_S. The symbols are relative planting dates for the 2 years with "0" representing the first planting date in 1979 and "9" the last planting date in 1980.

typical of earth observing satellites (e.g., Landsat MSS = 80 m).

For example, percent crop cover and leaf area index strongly influence the reflectance of radiation from crop canopies (11,21). Estimates of percent crop cover and leaf area index, obtained from multispectral data from satellites (e.g., Landsat MSS or Thematic Mapper) along with daily solar radiation from ground stations or meteorological satellites (1) will permit calculation of the amount of radiation intercepted by crops. This intercepted solar radiation variable combined with observed temperature and precipitation data and integrated over the growing season should account for much of the variation in corn yields. The multispectral data from satellites would form the basis for estimating crop growth and yields over regions where ground observations may be difficult or impossible to obtain.

SUMMARY AND CONCLUSION

We conclude from this research that estimating intercepted solar radiation using spectral data is a viable approach for merging spectral and meteorological data in crop yield models. This scheme is consistent with the spectral-physiological modeling approaches proposed by Wiegand et al. (22) but may avoid some of the problems associated with estimating LAI directly from spectral data. This concept may be extended to large areas using Landsat MSS data to estimate SRI for as many fields as are of interest. We are currently assembling the necessary data to evaluate this concept using Landsat MSS data from commercial fields in the U.S. Corn Belt.

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