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SPECTRAL ESTIMATES OF INTERCEPTED SOLAR RADIATION BY CORN AND SOYBEAN CANOPIES

K.P. GALLO, C.C. BROOKS, C.S.T. DAUGHTRY,
M.E. BAUER, V.C. VANDERBILT

Purdue University/Laboratory for
Applications of Remote Sensing
West Lafayette, Indiana

ABSTRACT

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 which are capable of providing accurate estimates of crop condition and yields. Initial tests of this concept using data acquired in field experiments included: different planting dates, populations, row widths, and soil types, at the Purdue Agronomy Farm are described.

The spectral variable greenness was associated with approximately 80 percent of the variation in LAI and percent soil cover for both corn and soybean canopies. The proportions of solar radiation intercepted (SRI) by corn canopies were estimated using either measured LAI or greenness. The proportions of SRI of soybeans were estimated using either measured percent cover or greenness. Both estimates when accumulated over the growing season accounted for approximately 65 percent of the variation in corn 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 corn grain yield were 0.68 for ECG models using greenness to estimate SRI. Similar relationships were developed for soybean yields.

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

I. INTRODUCTION

In recent years the world's food situation has emphasized the need for timely information on world-wide crop production. Relatively few countries, however, have reliable methods for gathering and reporting crop production information.

Remote sensing from aerospace platforms can provide information about crops and soils which could be useful to crop production forecasting systems. Although the feasibility of utilizing multispectral data from satellites to identify and measure crop area has been demonstrated (MacDonald and Hall, 1980), 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 potentially much 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 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 plant surface available for photosynthesis (Brown and Blazer, 1968; Dale, 1977).

In theory, the production of dry matter (DM) over time period t, beginning at emergence and ending at maturity, can be related to the proportion (P) of the incident light (SR) intercepted by the crop using the following equation from Steven (1982):

$$DM = \int_{e}^{m} E\ P\ SR\ dt \qquad [1]$$

E is the efficiency of conversion of solar energy into dry matter and typically ranges from 1 to 3 g/M Joule (Monteith, 1976). This equation can be used to predict dry matter 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 carbon dioxide. 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.

II. MATERIALS AND METHODS

A. DESIGN OF EXPERIMENT

Spectral and agronomic data were acquired at the Purdue University Agronomy Farm, 10 km northwest of West Lafayette, Indiana. Daily meteorological data were recorded at the cooperative National Weather Service station (West Lafayette 6NW) which was within 400 m of the fields. Incoming solar radiation was measured with an Eppley Precision Spectral Pyranometer and recorded as total Langleys/day (cal $cm^{-2}day^{-1}$). Daily maximum and minimum air temperatures were measured in a standard shelter. Soil moisture in the top 105 cm (depth of drainage tiles) was estimated using a soil moisture balance model (Stuff and Dale, 1978).

Corn. In both 1979 and 1980, a full season corn (*Zea may* L.) hybrid, Becks 65X, was grown on two soil types. When dry, the Chalmers silt loam (Typic Argiaquoll) had a dark gray (10YR 4/1) surface while the Toronto silt loam (Udollic Ochraqualf) had a light gray (10YR 6/1) surface. These two soils were spectrally distinct in both visible and near infrared reflectance factor (Kollenkark et al., 1981).

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. Within each soil type two completely randomized blocks with three plant populations (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, 22 May and 11 June 1980. Additional plots of 50,000 plants/ha were planted on 16, 29 May, 18 June, and 3 July 1980. These plots represented a wide range of planting dates and plant populations expected in corn fields in Indiana.

Soybeans. In 1978 the soybean (*Glycine max* (L.) Merr.) experiment was a randomized, complete block design which included three blocks, three cultivars (Amsoy 71, Wells, and Elf), three populations (111,000 and 185,000, 259,000 plants/ha), and three row widths (15, 45, and 90 cm) for a total of 81 plots.

In 1979 the soybean cultural practices experiment was a randomized, complete block design with two soil types (Chalmers silty clay loam and Russell silt loam, Typic Hapludalf), two blocks within each soil type, two row widths (25 and 76 cm), two cultivars (Amsoy 71, Williams), and three planting dates. Planting dates for the Chalmers silty clay loam were 10 May, 24 May, and 15 June. Poor drainage on the Russell silt loam delayed the planting dates on it to 24 May, 15 June, and 3 July.

In 1980 the experiment was a randomized, complete block design with two soil types (Chalmers silty clay loam, and Toronto silt loam, Udollic Ochraqualf, two blocks within each soil type, two row widths (25 and 76 cm), two cultivars (Amsoy 71, Williams), and seven planting dates (16 and 27 May, 12 and 18 June, and 7, 16, and 30 July).

B. AGRONOMIC MEASUREMENTS

Agronomic measurements, which were collected coincidentally with the reflectance factor measurements included: plant height, leaf area index (LAI), development stage, total fresh and dry biomass. Each sample was weighed immediately, separated into its components, dried at 75C and reweighed. Leaf area index (LAI) was calculated by multiplying the leaf area/dry leaf weight ratio of a random subsample of green leaves by the total dry green leaf weight and dividing by the soil area represented. Percent soil cover was determined by placing a grid over the vertical photograph and counting the intersections occupied by green vegetation. Visual assessment of the soil moisture and crop conditions were made during the spectral data collection. Crop condition assessment including evaluations of lodging, hail, insect and herbicide damage.

C. 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 (1979) describe the conditions and procedures for obtaining the RF data. The Exotech 100 has a 15 degree field of view and acquired data in the following wavelength regions: 0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1 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 degrees above the horizon.

The radiometer and a 35-mm camera were attached to a boom mounted on a pickup truck and elevated to 3.4m above the soil in 1978, 5.2m in 1979, and 7.6m 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. A color photograph which included the area viewed by the radiometer was taken vertically over each plot and used to determine percent soil cover.

D. DATA ANALYSIS

Two methods of estimating the proportion of solar radiation intercepted by corn canopies were examined. First, the proportion of intercepted radiation (SRIm) was described as a function of measured LAI using the following equation from Linvill et al. (1978):

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

This formula, which has the same form as Bouguer's Law, estimates the average daily proportion of solar radiation intercepted by a crop canopy as a function of LAI. The -0.79 is commonly termed an extinction coefficient. 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 as a function of the spectral variable greenness using the following equation:

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

where G is the green vegetation index or "greenness" for reflectance factor data. 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. This spectrally estimated proportion of radiation intercepted is called SRIs to distinguish it from SRIm which is estimated using measured LAI.

SRIs predicted as a function of greenness and SRIm predicted as a function of measured LAI 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 SRIs and SRIm were accumulated from planting to physiological maturity. Direct correlations of final grain yields with these accumulated indexes were examined.

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

$$ECGm = \sum_{i=plant}^{mature} (SRi/600)(SRImi)(WFi)(FTi) \quad [4]$$

where SR is the daily solar radiation in cal cm^{-2} day^{-1} and 600 is the approximate latent heat of water (cal cm^{-3}), WF is the ratio of daily evapotranspiration to potential evapotranspiration (Stuff and Dale, 1978), and FT is a daily temperature function (Coelho and Dale, 1980). For the spectral ECGs model SRIs was substituted directly for SRIm in Eq. [4].

An analysis sequence similar to that described above for corn was employed for soybeans using percent soil cover instead of LAI. Percent soil cover was used to describe the proportion of solar radiation intercepted by the soybean canopy because soybeans with a LAI of 2.0 in narrow rows cover more soil and intercept more radiation than soybeans with a LAI of 2.0 in wide rows.

III. RESULTS AND DISCUSSION

A. RELATION OF CANOPY REFLECTANCE AND AGRONOMIC VARIABLES

Agronomic variables 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 soil cover but relatively insensitive to soil color (Kollenkark et al., 1981). For corn for each year, and for the combined data, greenness predicted SRI better (higher R2) than LAI.

The relationships of the agronomic variables to the greenness transformation for corn in 1979 and 1980 and soybeans 1978 and 1979 are shown in Figures 1 and 2, respectively. For corn, planting date and plant population contributed to the scatter about the regression lines, but when included as terms in the regression models, they contributed very little additional information. Errors in measuring agronomic variables also may account for a portion of the scatter.

Other sources of variation in determining the interception of radiation by vegetation include solar azimuth and zenith angles, spectral properties of canopy elements, leaf area index, leaf angle distribution, leaf size and shape, leaf movement due to wind, wilting, and phototropism. Yet despite these many potential sources of variation, just one variable, leaf area index, is widely used to predict interception of solar radiation in plant canopies because it alone accounts for the majority of the variation. The extinction coefficient is generally assumed to be a constant. Norman (1980) 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 degrees) to -0.56 for high solar elevation angles (70 degrees). For soybeans Norman (1980) reported extincition coefficients ranging from -2.0 to -0.8 for low and high solar elevation angles, respectively. The extinction coefficients used in this research are within the range of values presented by Norman for approximately 45 degree solar elevation. Additional research is needed to characterize and model the changes in extinction coefficient if this approach is to be used quantitatively.

B. RELATION OF SPECTRAL VARIABLES TO YIELD

Corn is a determinant crop; that is, corn completes its vegetative development, producing all of its leaves, then shifts to reproductive development, producing and filling its grain. If corn grain yields are strongly related to the total amount of green leaf area present, then knowing the maximum LAI or maximum greenness of corn should be an important predictor of grain yields. Figure 3 illustrates this is not the case for our data. Grain yields are plotted as a function of maximum valves of greenness which occurred near tasseling. The poor relationship shown in Figure 3 emphasizes the limited valve of a single observation of greenness for predicting corn yields. Although the soybeans grown in these experiments continued their vegetative growth during their reproductive development, analysis of data from Kollenkark et al. (1982) shows that single observations of greenness also were poor predictors of soybean yields.

A more important and useful indicator of grain yields is the seasonal duration of LAI and not simply the maximum LAI achieved. Two variables, the summed values of SRIm and SRIs, represent the proportions of the solar radiation impinging on the corn or soybean field that was intercepted by the crop canopy and thus were potentially available for photosynthesis (Figure 4). Both estimates of intercepted solar radiation were associated with approximately 65 percent of the variation in corn 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 reseachers have demonstrated for various crops that the reduction in crop growth is proportional to the reduction in the ratio of evapotranspiration (ET) to potential evapotranspiration (PET) (Dale, 1977; Hanks, 1974; Hill et al, 1979; Kanemasu et al, 1976). Coelho and Dale (1980) combined temperature and moisture stress with an estimate of intercepted solar radiation using measured LAI in an Energy-Crop Growth (ECG) 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 SRIs or SRIm to estimate intercepted solar radiation are plotted with grain yields in Figure 5. Both of the ECG models have slighty larger coefficients of determinations (R2) than the SRIs and SRIm models. Although the ten planting date-years represented a range of temperature and day length regimes, significant water stress was not evident among the treatments. In this case, both of the intercepted radiation variables (SRIs and SRIm) alone were nearly as highly correlated to yields as the meteorological (ECG) models. In climatic regions 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.

Combining spectrally derived estimates of SRIs with meteorological models should permit implementation of crop growth and yield models for large areas. A spectral-meteorological system of crop forecasting could exploit the advantages of frequent temporal sampling of weather data (e.g. daily or hourly) and the high spatial resolution typical of earth observing satellites (e.g. Landsat MSS).

An example of this concept, showing how multispectral data from satellites could be used to estimate crop yields, is presented in Figure 6. Percent soil cover and leaf area index strongly influence the reflectance of radiation from crop canopies. Estimates of percent soil cover and leaf area index, obtained from Landsat MSS data along with daily solar radiation from ground stations or meteorological satellites 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 crop yields. Nevertheless, agronomic variables predicted as a function of the greenness transformation permit the concepts and models developed at the Purdue Agronomy Farm to be used in situations where only spectral data may be available.

IV. SUMMARY AND CONCLUSIONS

Spectral and agronomic data were acquired throughout several growing seasons for corn and soybeans. Two variables, SRIm and SRIs, representing the proportions of solar radiation potentially available for photosynthesis were estimated. SRIm was calculated by Bouguer's Law using measured LAI while SRI was estimated using the spectral variable of greenness.

Five methods or models for predicting yields were examined in this research. One method using a single observation of the maximum greenness had the lowest correlation with grain yields. Methods which integrated spectral or meteorological variables over the growing season (e.g., SRIm, SRIs) accounted for over half of the variation in grain yields. Models which simulated the daily effects of weather on crop growth (e.g., ECGs, ECGm) had the highest correlations to grain yields.

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. (1979) 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.

V. ACKNOWLEDGMENTS

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VII. AUTHOR BIOGRAPHIES

Kevin Gallo is a Graduate Research Assistant with the Laboratory for Applications of Remote Sensing at Purdue University. He received his B.S. in meteorology from Northern Illinois University in 1978, his M.S., in agronomy (agricultural meteorology) from Purdue in 1981, and is currently working on his Ph.D.. Mr. Gallo is a member of the American Meteorological Society and the American Society of Agronomy.

Christopher Brooks is a Graduate Research Assistant with the Laboratory for Applications of Remote Sensing at Purdue University. He received his B.S. in Soils from Washington State University in 1977, his M.S. in Plant and Soil Science from the University of Massachusetts in 1980, and is currently working on his Ph.D.. Mr. Brooks is a member of the American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, and several honorary societies.

Dr. Craig Daughtry is a research agronomist with the Laboratory for Applications of Remote Sensing at Purdue University. He has B.S. and M.S. degrees in agronomy from the University of Georgia and a Ph.D. in crop physiology from Purdue University. He is a member of the American Society of Agronomy, Crop Science Society of America, American Society of Photogrammetry and several honorary societies.

Dr. Marvin E. Bauer is a Research Agronomist at Purdue University and holds degrees from Purdue University and the University of Illinois. He is program leader of Crop Inventory Research at the Laboratory for Applications of Remote Sensing. He has had key roles in the design, implementation and analysis of results of several major remote sensing experiments including the 1971 Corn Blight Watch Experiment and the Large Area Crop Inventory Experiment. His research is on the spectral properties of crops in relation to their agronomic characteristics and the development and application of satellite spectral measurements to crop identification, area estimation and condition assessment.

Dr. V. C. Vanderbilt is with the Laboratory for Applications of Remote Sensing as a research engineer developing physically based analyses and mathematical models of remotely sensed biological systems. He has the usual degrees from Purdue University in electrical engineering.

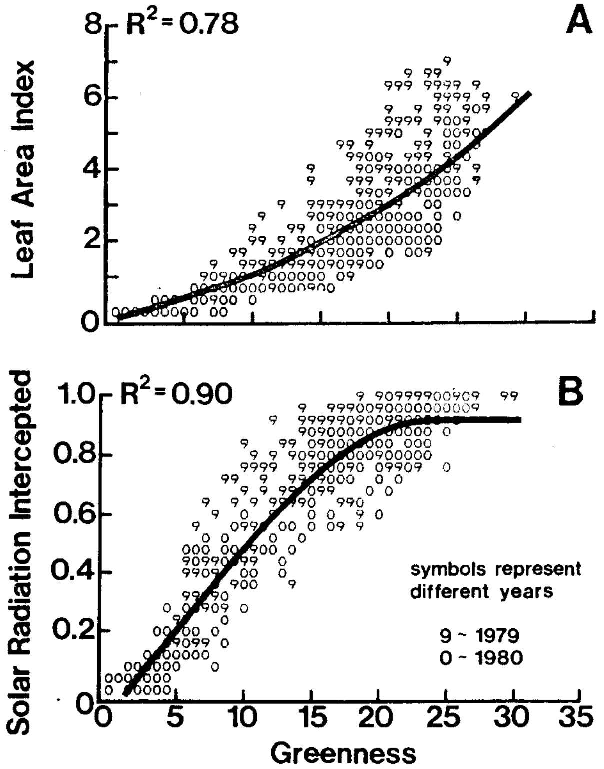

Figure 1. Relationships of leaf area index (LAI) solar radiation intercepted (SRIs) to the spectral variable greenness. LAI = (-0.1364 + 0.0647 Greenness + 0.0047 Greenness^2). SRIs = (-0.1613 + 0.0811 Greenness - 0.0015 Greenness^2).

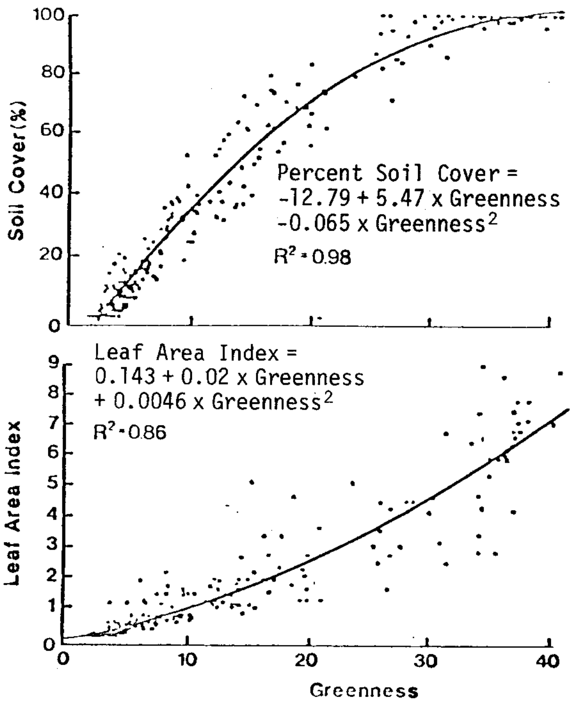

Figure 2. Percent soil cover and leaf area index of soybeans as a function of greenness.

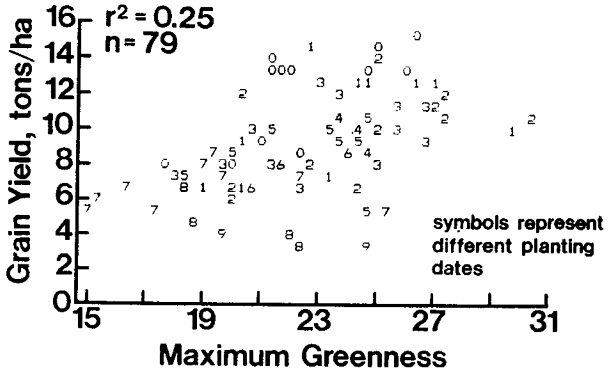

Figure 3. Corn grain yields as a function of maximum greenness.

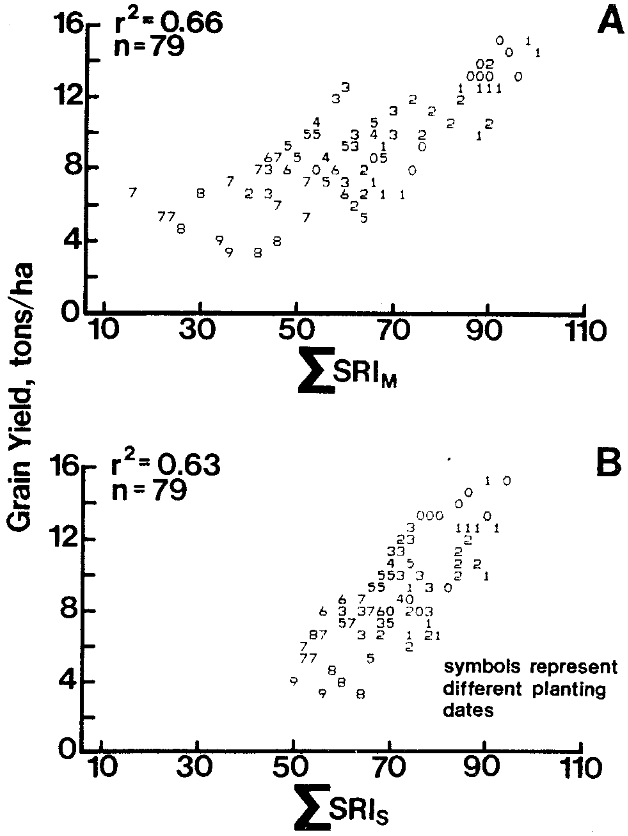

Figure 4. Corn grain yields as function of the accumulated proportions of solar radiation intercepted by the corn canopies. SRIm is estimated using measured LAI and SRIs is estimated using spectral data. The symbols are relative planting dates for the two years with "0" representing the first planting date in 1979 and "9" representing the last planting date in 1980.

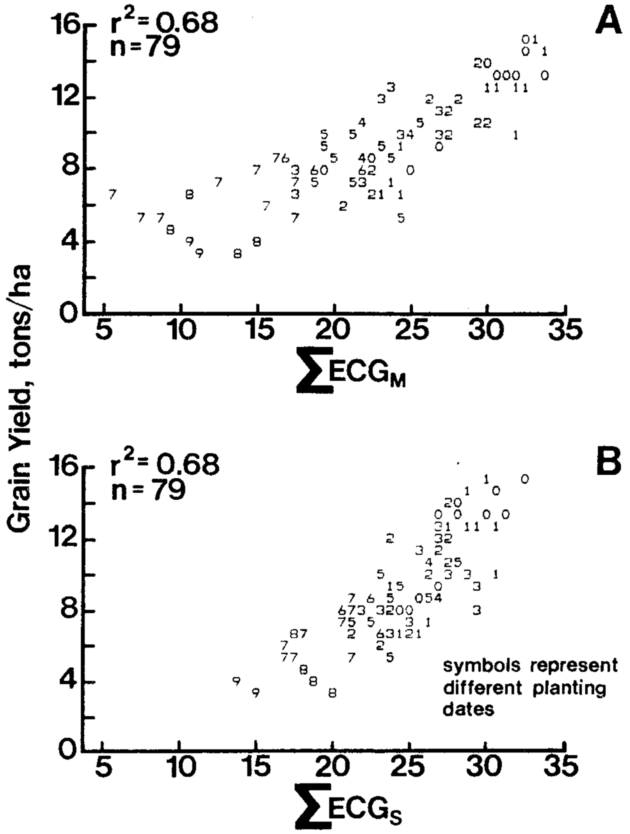

Figure 5. Corn grain yields as a function of the accumulated Energy-Crop Growth variable. ECGm is calculated using SRIm and ECGs with SRIs. The symbols are relative planting dates for the two years with "0" representing the first planting date in 1979 and "9" representing the last planting date in 1980.

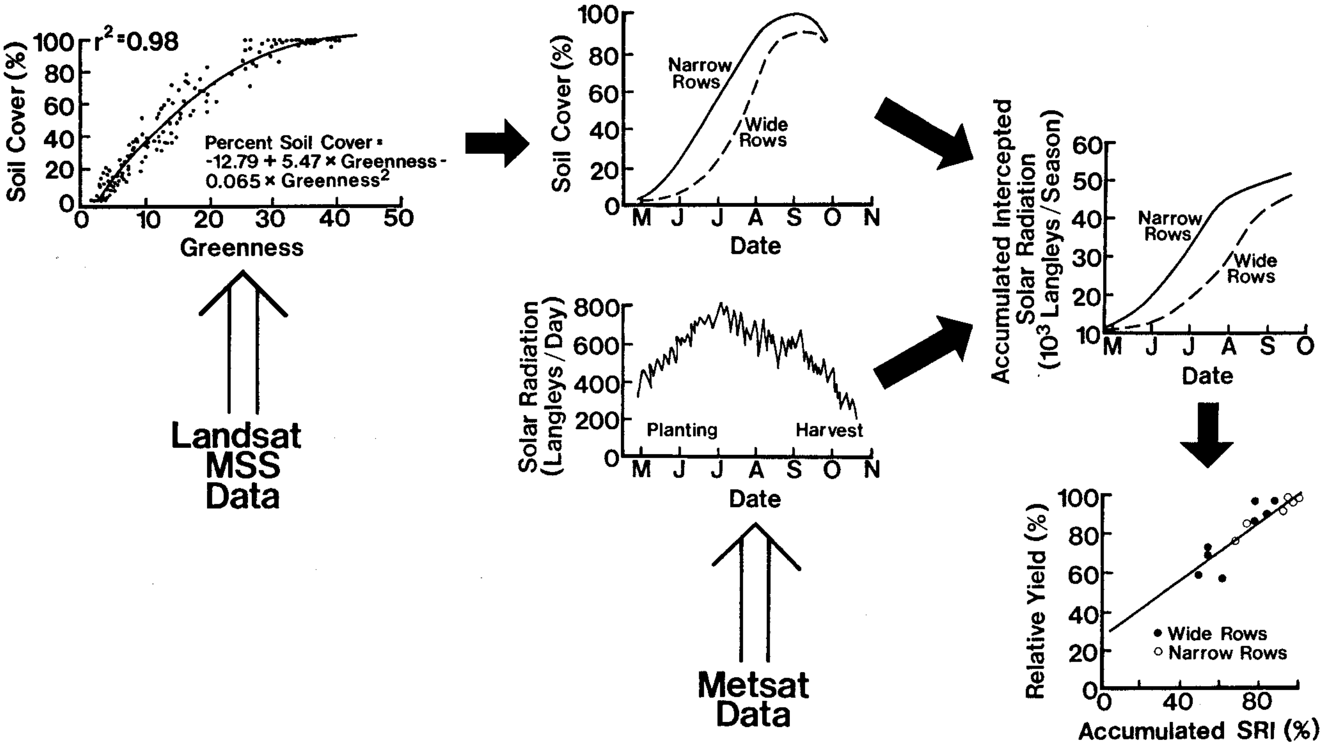

Figure 6. An overview of the concept proposed for combining spectral and meteorological data in crop yield models.