Development of Agrometeorological Crop Model Inputs from Remotely Sensed Information

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***Abstract*—The goal of developing agrometeorological crop model inputs from remotely sensed information (AgRISTARS Early Warning/Crop Condition Assessment Project Subtask 5 within the U.S. Department of Agriculture (USDA)) provided a focus and a mission for crop spectral investigations that would have been lacking otherwise. Because the task had never been attempted before, much effort has gone into developing measurement and interpretation skill, convincing the scientific community of the validity and information content of the spectral measurements, and providing new understanding of the crop scenes viewed as affected by bidirectional, atmospheric, and soil background variations. Nonetheless, experiments conducted demonstrate that spectral vegetation indices (VI) a) are an excellent measure of the amount of green photosynthetically active tissue present in plant stands at any time during the season, and b) can reliably estimate leaf area index (LAI) and intercepted photosynthetically active radiation (IPAR)—two of the inputs needed in agrometeorological models. Progress was also made on using VI to quantify the effects of yield-detracting stresses on crop canopy development. In a historical perspective, these are significant accomplishments in a short time span.**

Spectral observations of fields from aircraft and satellite make direct checks on LAI and IPAR predicted by the agrometeorological models feasible and help extend the models to large areas. However, newness of the spectral interpretations, plus continual revisions in agrometeorological models and lack of feedback capability in them, have prevented the benefits of spectral inputs to agrometeorological models from being fully realized.

I. BACKGROUND

IN 1976, a decision was made in the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) to launch an effort to develop an agrometeorological model for forecasting wheat (*Triticum aestivum* L.) yields. At the first meetings of the scientists and administrators to define and plan the project, there was limited awareness and even skepticism about the possibilities of using remote spectral observations in crop models, except for one or two individuals who had been exposed to the Large Area Crop Inventory Experiment (LACIE) [34]. However, information such as the flow chart of Fig. 1 illustrated and interrelated spectral data and model inputs [53], [54] and provided evidence of technical feasibility.

Once remote observations were accepted as a legitimate part of the effort, the Wheat Yield Project gave a sense of mission and direction to the utilization of spectral measurements. The project also exposed additional scientists to spectral observations. The early decision of the project's leadership to acquire and disperse handheld radiometers [51] and data loggers (Polycorders®)[1] to the project's participants, and the workshop held on their use [15] were important contributors to the experiments that have been conducted under the impetus of and with at least partial funding from the ARS Wheat Yield Project.

When the multi-agency AgRISTARS effort began in 1979, the wheat modeling effort became part of the ARS's contribution to it. A subtask with the title of this paper was established within the Early Warning/Crop Condition Assessment Project managed by Glennis Boatwright of the ARS at Houston. The spectral research was concentrated at Weslaco, Texas; Phoenix, Arizona; and Beltsville, Maryland. Related additional experiments were conducted at Sidney, Montana; Mandan, North Dakota; Akron and Ft. Collins, Colorado; and Bushland and Lubbock, Texas. Personnel of the Statistical Reporting Service (SRS) of the USDA at Fort Collins, Houston, and Washington participated in various studies [28], [29], [35]. The crop modeling effort was centered at Fort Collins, Colorado, and Temple, Texas. The scope of the effort was to develop and test spectral data products for crop response to management variables, early warning and crop condition alarms and assessments, and crop growth and yield model inputs.

The purpose of this paper is to overview the research conducted within the USDA relevant to developing spectral inputs to agrometeorological crop models and to highlight some of the progress. Similar work conducted at Purdue University, Kansas State University, University of Nebraska, and at the Johnson and Goddard Space Flight Centers under NASA sponsorship will generally not be covered.

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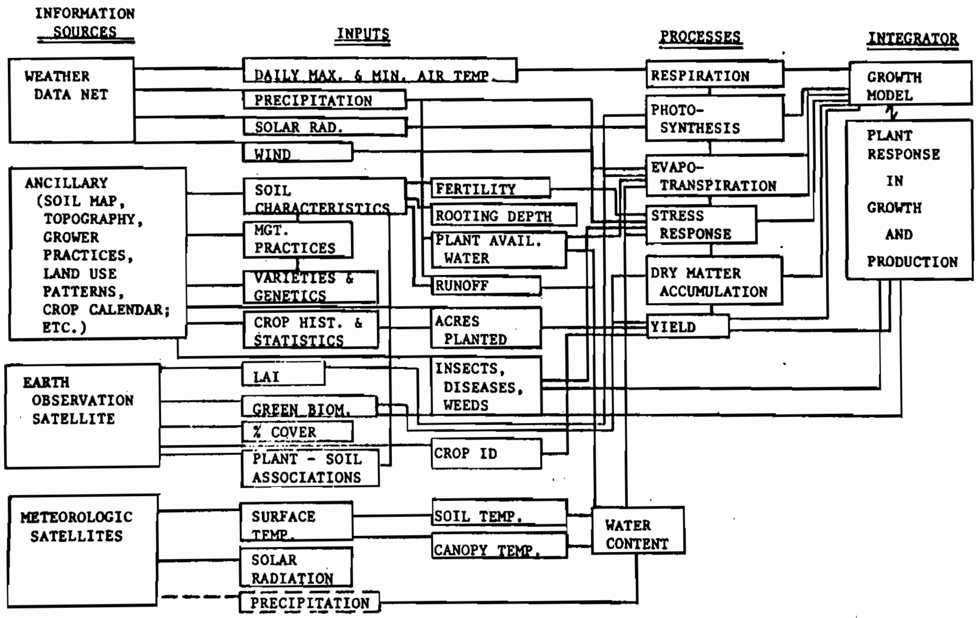

Fig. 1. Information sources, inputs, and plant processes for agrometeorological plant growth and yield models (after [59], [61]).

II. Introduction

The use of remotely sensed information in agrometeorological models depends on its availability compared with traditional data sources, and on the expertise and biases of the individual or group applying the model(s). Herein, we define remotely sensed information as noncontact observations in one or more wavelengths in the range 0.35 μm (lower limit of visible light) through 14 μm (thermally emitted electromagnetic radiation). Microwave (1–30 cm wavelength observations would be useful but are not generally available. The agrometeorological crop models in mind are those that: a) use soil properties (rooting depth and plant available water) and daily increments of weather data (temperature, precipitation, and insolation) as inputs to subroutines that simulate various plant processes (phenological or ontogenetic development, photosynthesis, respiration, evapotranspiration, dry matter accumulation); b) are designed to describe crop behavior on a field scale; c) are capable of simulating the crop from planting to maturity; and, d) estimate yield of the salable plant parts. Models in this category include TAMW [33], CERES [46], and SORGF [32].

Remotely sensed information can be used in two principal ways in conjunction with an agrometeorological model. One way is to provide surrogate estimates of one or more specific inputs that "drive" the model, e.g., leaf area index (LAI)[2] or intercepted[3] photosynthetically active (0.4–0.7 μm) radiation (IPAR). The other way is to provide independent feedback to override and reset the model simulated canopy development or yield estimates [43], [55], [59], [60], [61]. In the first approach the spectral data provide an alternative way of acquiring the necessary inputs for the model. In the second approach, for example, the LAI simulated by the model could be replaced with LAI estimated by handheld, aircraft- or spacecraft-mounted sensors viewing the same field(s). Since such feedback capability is lacking in most agrometeorological models at present, there is interest in a third way of using spectral data—as an independent direct assessment of crop condition and probable yield.

The information needed for any of the above spectral approaches is acquired by directly observing the plant canopies. Thus, the spectral or remote sensing approach takes advantage of the fact that the plants integrate their soil and aerial environments and express their development, stress response, and yield capabilities through the canopies achieved [60], [61]. Vegetation indices [15], [17], [19], [24], [29], [35], [39], [43], [49], [57] calculated from the spectral observations capture information on canopy development and condition; respond to past and current management (residual fertility, tillage, crop residue management, and cultural practices) and soil profile differences within and among fields that are not easily included in agrometeorological models; and provide a means of quantifying canopy development in response to stresses (current nutritional level, nematodes, diseases, herbicide residue, atmospheric pollutants, drought) [59], [61]. Thus, the use of spectral observations in conjunction with an agrometeorological model increases confidence that the model is tracking the actual behavior of plants in individual fields [62]. This confidence factor is extremely important. Crop models will not be applied for real world decisions unless consistently reasonable outputs can be expected.

[2]The ratio of the area of green leaves to the ground area occupied on the whole field basis.

[3]Typically, sensors sensitive to the PAR wavelength interval are used to measure the light incident (I) on the canopy, the light transmitted (T) through the canopy to the ground, the light reflected (R) from the plants and soil, and the soil (R_s). Intercepted PAR is defined as $(I-T)/I$ and absorbed PAR (APAR) as $(I-T-R + TR_s)/I$. Sometimes investigators report IPAR and sometimes APAR, but they differ by only a few percent for a canopy that fully covers the ground. They can differ more at low vegetative cover where surface wetness and organic matter and mineral content of the soil affect albedo in the PAR wavelengths.

III. Progress Under the ARS Wheat and AgRISTARS Projects

The experiments have dealt with a large set of issues that contribute directly or indirectly to use of spectral data in models by documenting relationships that exist, providing new understanding of scene and atmospheric behavior, acquiring data sets for testing hypotheses and relationships, convincing the scientific community of the validity and information content of the spectral measurements, developing interpretation skill and meaning, and providing insights to support integration of spectral observations into crop models. This whole spectrum of activities was necessary to a) establish the scientific validity of new measurements and concepts, b) acquire the necessary expertise and equipment to use the technology, and c) change traditional or institutionalized procedures.

By 1981 the AgRISTARS effort was well underway. In October of that year the senior author suggested the following as viable research objectives in a memo to colleagues.

1) "Calibration of LAI, percent cover, and other agronomic characteristics versus vegetation indices; checking their geographic generality; and, determining the 'best' equation forms.
2) "Testing the above relations within and among crop species to determine, for example, whether the 'calibrations' are the same for the temperate cereals, soybeans and cotton, sorghum and corn... and pinpointing canopy 'architecture' and other reasons for differences.
3) "Understanding the properties of vegetation 'greenness' as expressed by the vegetation indices.
4) "Testing whether LAI is a necessary characterizer of canopies for light interception, or whether percent cover (PC) is adequate.
5) "Developing spectral measures of stress and comparing them with traditional ones, or defining and explaining new spectral ones.
6) "Developing spectral surrogates of LAI, biomass, or genetic canopy coefficients for use in growth and yield models, or to reinitiate or override these models.
7) "Compiling data sets to test whether we can go directly from spectral measurements to intercepted light.
8) "Testing spectral models of yield versus those from agrometeorological and ecological-physiological models.
9) "Determining the effect of atmospheric corrections (sun angle, path radiance, haze) on the vegetation indices.
10) "Developing procedures to achieve agreement between space and ground-observed vegetation and soil indices."

Again, the list illustrates the diversity of activities that needed to proceed simultaneously to develop, understand, and use vegetation indices, the main vehicle for providing spectral inputs to models. Despite this great diversity, and lack of a coordinated plan for research on such objectives significant progress was made.

Subject matter areas that were researched and documented included:

1) Spectral-agronomic relations [1], [4], [5], [10], [20], [43], [49], [52], [55].
2) Spectral-temporal and spectral-phenological relations [2], [30], [37], [45], [48], [49].
3) Spectral transforms, vegetation and soil indices, their relation with canopy characteristics (LAI, green biomass, percent cover, chlorophyll content, phytomass), and interpretation techniques [11], [15], [19], [35], [37], [39], [49], [52], [57], [59], [60]–[62].
4) Wavelengths in addition to the Landsat wavelength intervals (0.5–0.6, 0.6–0.7, 0.7–0.8, and 0.8–1.1 μm) and their utility and information content [15], [17], [30].
5) Procedures to achieve agreement between space (top of atmosphere) and ground-observed reflectance factors [17], [18], [40]–[42], [44].
6) Scene spectral modeling including effects of atmosphere, sun and view angles, and planting configurations on observations [14], [23], [26], [27], [37], [38], [47], [48].
7) Spectral measures of stress [16], [17], [21], [22], [36], [58].
8) Spectral estimates of yield [3], [5], [12], [13], [36], [50], [52], [60].
9) Spectral inputs or surrogates for agrometeorological models [9], [10], [43], [45], [55], [59], [60]–[62].
10) Plant development scale comparison [6].

In addition, USDA researchers made their field plots available to other scientists for experimental measurements [25]–[27], [31], [49].

Selected exemplary figures, tables, and equations from these publications illustrate the progress that has been made. Fig. 2 (after [43]) relates the LAI of grain sorghum on five dates to above-ground phytomass. Since the spectral observations are responding to the chlorophyll containing parts of the crop canopy [60], there is a close relation between LAI and above ground phytomass as long as the "stems" consist of leaf sheaths. But, when a true stem and then a head and grain develop, the latter contain most of the phytomass, and the relation between LAI and phytomass deteriorates. Whereas spectral vegetation indices relate less and less well to wet and dry phytomass as crops approach maturity, the VI relate well to LAI throughout the life cycle of the crop. In the agrometeorological models, LAI is used to characterize crops for penetration and interception of photosynthetically active radiation in the photosynthesis and growth subroutines, and to partition insolation between evaporation of water from the soil and transpiration from the plants [55]. Thus, remote estimates of LAI can be direct inputs to the models.

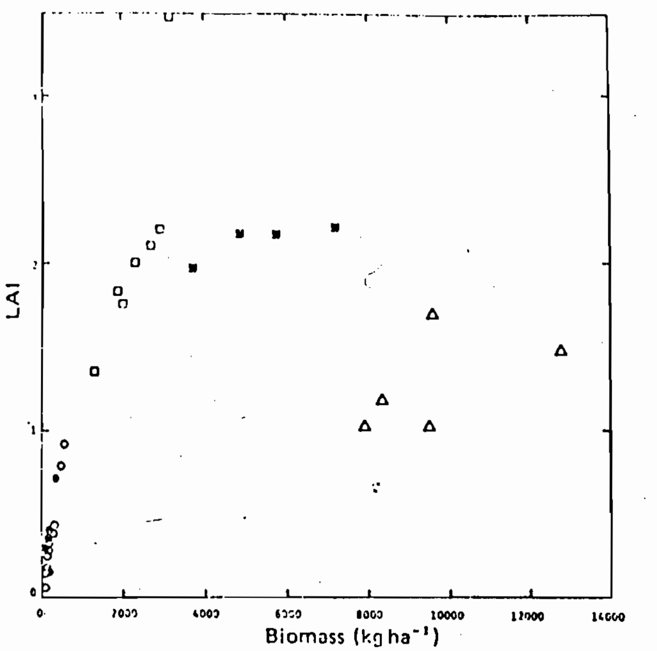

Fig. 2. Plot of sorghum leaf area index measurements versus above ground biomass measurements for five Landsat overpass dates during 1976 growing season in Bell County, TX. The correlation coefficients by date were: ○, May 3, 1976, 0.996**; ●, May 21, 1976, 0.990**; □, June 8, 1976, 0.946**; ■, June 26, 1976, −0.247; △, August 1, 1976, 0.459 (**, statistically significant at the 0.01 probability level) (after [43]).

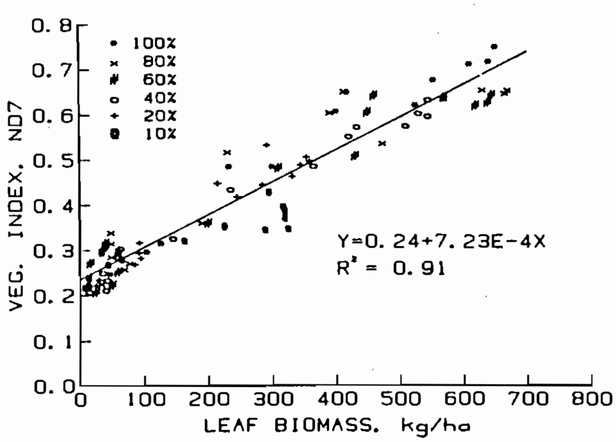

Fig. 3. Normalized difference vegetation index (ND7) versus leaf biomass for six spring wheat stand densities, expressed as a percentage of normal seeding rates (after [4]).

Many researchers have verified that vegetation indices—differences, ratios, and linear transformations of spectral reflectance or radiance observations [24], [39], [49], [15], [17], [19], [35], [48]—relate to crop canopy "greenness" [1], [4], [10], [17], [30], [37], [39], [43], [49], [52], [55], [60]. As an example of one vegetation index, Fig. 3 (after [3]) shows that leaf biomass is related to the normalized difference (ND) defined by (MSS7 − MSS5)/(MSS7 + MSS5) where MSS5 and MSS7 denote the reflectance in visible red (0.6–0.7 μm) and reflective infrared (0.8–1.1 μm) wavelengths. These two wavelengths correspond to Landsat multispectral scanner (MSS) bands 5 and 7, respectively. Data such as those in Fig. 3 have been influential in convincing the scientific and user communities that spectral observations can be used to estimate important agronomic characteristics of crops. This

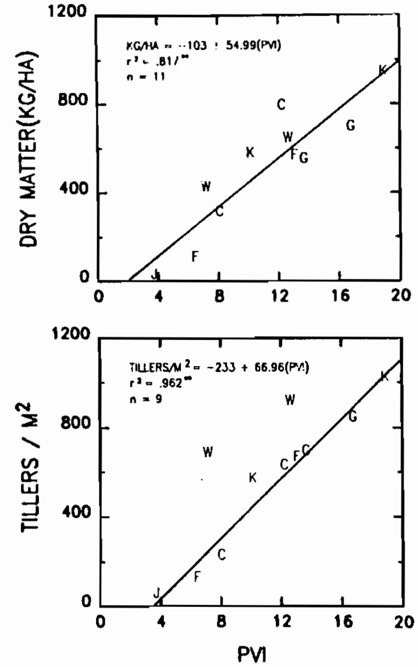

Fig. 4. Relation between perpendicular vegetation index (PVI) and two plant characteristics (tillers per square meter and dry matter, kilograms per hectare) during the fall growth period of the ARS Wheat Yield Project fields in the 1977–1978 season. Fields are located in Keith (K) Co., NB; Grant (G) Co., OK; Washington (W) Co., CO; Finney (F) Co., KS; Greeley (E) Co., KS; and Jewel (J) Co., KS.

accomplishment of the AgRISTARS effort should not be underrated. It was a necessary step in getting a new technology accepted; without the acceptance there would be no use. It is an accomplishment shared jointly by the NASA-funded and the USDA-funded research highlighted herein.

The value of the vegetation indices is that they condense observations in two or more wavelengths to a single number that relates well to the amount of photosynthetically active tissue [60], [62]. Thus the VI relate well to LAI, percent cover by green vegetation, leaf weight, plant population, green or dry biomass of nonstemmy vegetation, chlorophyll content per unit area, and consequently, to the crop's light interception capacity. Lautenschlager and Perry [29] and Perry and Lautenschlager [35] showed that a number of the vegetation indices are mathematically equivalent. Jackson *et al.* [17] described their sensitivity to atmospheric effects.

The relation between the perpendicular vegetation index (PVI) derived from Landsat-2 observations adjusted for solar zenith angle and atmospheric haze and two groundtruthed plant parameters, tillers per square meter and dry matter (kilograms per hectare) collected in fields of the ARS Wheat Project is shown in Fig. 4. The data are for the fall growth period preceding winter dormancy. There are two observation dates for five of the fields and one observation date for the Jewel Co., Kansas, field.

The coefficient of determination between PVI and tillers per square meter for the sites except Washington Co., Colorado, is 0.96 whereas it is 0.82 between PVI and dry matter including the Washington Co., Colorado, field. The slopes of the regression equations indicate there are 67

TABLE I

COEFFICIENTS OF DETERMINATION BETWEEN 9 SPECTRAL MEASURES AND ln LAI, GRAIN YIELD, AND IPAR (PART A) AND AMONG THE 3 DEPENDENT VARIABLES (PART B)
(After Wiegand and Richardson [60].)

(A) Veg. index or MSS band	ln LAI	Yield kg ha^{-1}	IPAR %
		r^2	
PVI	.601**	.676**	.526**
GR	.570**	.665**	.524**
GRw	.551**	.661**	.487**
RVI	.573**	.617**	.504**
ND	.619**	.670**	.565**
MSS4	(-)[a/] .446**	(-) .447**	(-) .479**
MSS5	(-) .543**	(-) .521**	(-) .548**
MSS6	.000	.018	.005
MSS7	.284**	.387**	.203*
(B)			
ln LAI	1.000		
Yield	.827**	1.000	
IPAR	.962**	.773**	1.000

** Significant at P=.01.
* Significant at P=.05.

a/ Negative signs designate variable pairs that were inversely related.

tillers/m^2 per unit PVI and 55 kg/ha dry matter per unit PVI. Such relations between spectral and agronomic data may prove useful for monitoring crop growth. The fact that the relation between tillers per square meter and dry matter, $r^2 = 0.83$ (not shown) was no better than between the top of the atmosphere Landsat observations and these parameters individually indicates that the spectral samples represented these fields as well as the plant samples did.

Ability to estimate tiller population spectrally is useful for establishing the plant population needed as initial input to the models. (For a short time after emergence only primary tillers exist, so the tiller population is the plant population.) Also, the number of tillers estimated soon after spring greenup compared with the number prior to winter dormancy indicates the number that survived the winter. The tiller estimates may also be of value in checking on the number estimated by the agrometeorological model used; number of tillers has not been easy to mimic accurately in agrometeorological models.

Wiegand and Richardson [60] summarized the coefficients of determination among nine spectral measures (five VI and the four MSS bands) and LAI, grain yield, and intercepted photosynthetically active radiation (IPAR) for grain sorghum during the grain filling stage (Table I, part A). The coefficients of determination among the dependent variables LAI, YIELD, and IPAR are also presented (part B). The vegetation indices as they appear in the table, are the perpendicular vegetation index (PVI), the greenness (GR) using universal coefficients, a greenness derived using local (Weslaco) scenes (GRw), the ratio vegetation index (RVI), and the normalized difference (ND). The vegetation indices are superior to the individual Landsat MSS bands, and for the data set presented, ND and PVI related more closely to LAI and grain yield than did the other vegetation indices. Coefficients of determination between yield and LAI (0.827) and between yield and IPAR (0.773) illustrate the predictability of yield through spectral observations of crop canopies.

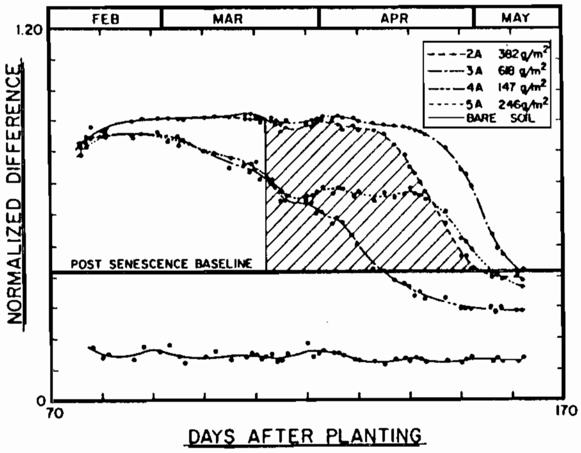

Fig. 5. The normalized difference (ND) versus time after planting for four Produra wheat fields with widely varying yields and a bare soil plot. The shaded portion under the curve for plot 2A is a graphic representation of the integration technique described in the text (after [36]).

On most of the Great Plains, water deficits and other constraints usually prevent rainfed wheat from achieving a canopy dense enough to fully intercept the light. But since seeding rates and management practices are tuned to location specific climate and soil constraints, the harvest index of wheat is remarkably constant even on the western Great Plains [3]. Because high yields cannot be achieved unless the crop canopy development is sufficient to intercept most of the incident insolation during the reproductive phase, the spectral measurements frequently correlate well with yield [60]–[62]. For example, Tucker *et al.* [50] reported that there was a five-week period, from stem elongation through anthesis, over which the ND explained approximately 64 percent of the grain yield variation of wheat. Aase and Siddoway [3] reported that the highest correlations between spectral indices and yield for wheat were obtained from stem elongation through watery ripeness of the grain. The reason the relations are best through early grain filling is that the [green] leaf area index reaches a maximum at about boot stage and declines throughout grain filling. Consequently, the later in grain filling the spectral observations are made, the more the photosynthetically inactive tissue dominates the observations and the relationship degrades.

Pinter *et al.* [36] used a somewhat different approach (see Fig. 5). They summed the normalized differences daily for the period from heading to full senescence for all ND above the base value for harvest-ready (fully senescent) crops of wheat and barley. Thus, they took into account not only the greenness of the canopy but also its persistence. For Produra wheat whose canopy development had been affected by timing and amount of irrigation water applied, the summed ND accounted for 88 percent of the yield variation. However, because the duration of grain filling in temperate cereals, including wheat, is temperature dependent [56], any method analogous to leaf area duration cannot hold across environments. [8].

Temporal spectral measurements, such as those shown in Fig. 5, are valuable for following the pattern of canopy development. For example, a leveling off in vegetation index during the period of normal, rapid development of the canopy may well correspond to a gradual depletion of soil water, especially if a rapid rise in the VI is observed following a known rainfall event. The vegetation index behavior would correspond to a decrease in growth (production of leaf and canopy) during a water stress period and "boom" growth upon relief by the rain. For wheat and other temperate cereals, the decline in VI following anthesis can be quantified into a senescence rate (VI day^{-1}) that can be related to agronomic and environmental conditions. Idso *et al.* [13] have even proposed that yields be estimated from senescence rates.

Wiegand and Richardson [60], [62] have proposed equations that interrelate the information conveyed by plant canopies about their development (or restraint from development by stresses), light interception capability, and yield performance. The equations are

$$\frac{\ln \text{LAI}}{\text{VI}} \times \frac{\text{IPAR}}{\ln \text{LAI}} = \frac{\text{IPAR}}{\text{VI}} \tag{1}$$

$$\frac{\ln \text{LAI}}{\text{VI}} \times \frac{\text{Yield}}{\ln \text{LAI}} = \frac{\text{Yield}}{\text{VI}} \tag{2}$$

where VI denotes any one of several spectral vegetation indices available, IPAR is intercepted photosynthetically active radiation, and yield is grain yield.

Essentially, the integral VI are estimates of integral intercepted solar radiation which Daughtry *et al.* [7] and Hatfield *et al.* [9] have shown can be estimated spectrally. Since the IPAR versus ln LAI relations, available in the literature and already in use in the agrometeorological models, can be transferred directly to (1) it becomes possible to estimate IPAR remotely. This means in effect that IPAR generated by the models can be checked by direct spectral observations. Where the relation between LAI and VI is known from previous studies, such as it is for wheat, the VI's can also serve to check on the model's estimates of LAI.

From historical Landsat or the currently available NOAA meteorological satellite data, the relation between yield and VI can be established on field (Landsat) or county or crop reporting district synoptic scales (NOAA) from the VI observations those sensors provide and the yield data reported annually by the Statistical Reporting Service. Wiegand *et al.* [58] and Wiegand [59] reported such a relation for grain sorghum (*Sorghum bicolor* L., Moench) in South Texas, established during grain filling of the crop. By definition the difference between the spectral estimate for the current year and the long term average is the production deviation from the average. Such information when available in advance is useful in preparing to harvest, transport, store, and market the crop.

TABLE II
REMOTELY SENSED INPUTS OR FEEDBACK TO AGROMETEOROLOGICAL MODELS GROUPED BY MODEL SUBROUTINES
(After Wiegand [59], [61].)

Model Subroutines	Remotely Sensed Input or Check
Growth or dry matter accumulation	VI[a/]--spectral surrogate of green biomass --spectral profile[b/] --growth rate
Photosynthesis	VI--spectral surrogate of LAI for light absorption estimate Spectral estimates of IPAR
Evapotranspiration	BR or SLI[c/]--albedo, surface wetness --ground cover for partitioning evaporation and transpiration Tc-Ta[d/]--as related to ratio of actual to potential evapotranspiration, E/Ep
Phenology	Spectral profile--emergence or green-up date, maximum greenness date Tc--in lieu of air temperature to pace ontogenetic events
Stress	VI--Canopy "greenness" and magnitude vs. normal; senescence rate Tc-Ta--stress severity diagnostic, or in crop water stress index, (1-E/Ep)
Yield	VI--near maximum canopy development or early in grain filling; spectral profile integrals

a/ VI = spectral vegetation indices GR, PVI, ND, etc. (see text)

b/ Spectral profile = vegetation index vs. time (see fig. 5, e.g.)

c/ BR, SLI = brightness and the soil line index, spectral indices dominated by soil background. (see Kauth and Thomas [24]; Wiegand and Richardson, [57]).

d/ Tc is canopy temperature; Ta is air temperature

The possibility of quantifying stress effects on yields through the canopy manifestations is an exciting one. Although the literature on crop stresses is voluminous, ways to relate stresses meaningfully to yields have been lacking [58]. Spectral observations to quantify stresses and relate them to yield merit further emphasis.

Table II summarizes additional opportunities to augment agrometeorological models with remote spectral observations. The table is organized by the subroutines (photosynthesis, growth or dry matter accumulation, evapotranspiration, phenology, stress, and yield) usually found in the growth/yield models. A number of the possibilities are hypothetical in that there is no known test in the literature, although tests are technically feasible. Others depend, for acceptance, on the outcome of tests of the relations expressed by (1) and (2). Still others depend on the availability of suitable data sets.

A point worth making is that there is no past experience on using and incorporating remotely sensed observations into crop growth/yield models because such observations have not been previously available, their usefulness had not been demonstrated, or operational products were not produced. For example, NOAA can provide surface temperature (canopy temperature when the canopies are well developed) and is developing precipitation estimates from the Advanced Very High Resolution Radiometer (AVHRR) aboard the operational meteorological satellites [63]. Thus the models and operational products will evolve gradually with experience.

An important aspect of any successful effort will be data bank and data base management. Current research on geographic information systems will be vital to successful operational application of crop models. As shown in Fig. 1 there are myriad sources of relevant information that could be acquired, archived, merged and processed to extract that needed to execute models. With current pressures on food, fuel, fiber, and forage vegetation resources, the scientists involved are working on projects with global consequences. In general, we feel that many of the candidate spectral inputs for Table II are now ready for testing and adaptation for incorporation into crop growth/yield models.

High priority needs to be placed on producing algorithms for resetting and continuing the execution of agrometeorological models when remotely sensed canopy observations are used as feedback to the models and on development of workable geograhic information systems.

IV. Summary

The progress made in developing and using spectral information promises to augment and enhance agrometeorological models by providing direct evidence of canopy condition that can be interpreted in terms of plant population, LAI, or IPAR for direct use in the models, or as feedback to them. Thus, use of spectral observations in conjunction with agrometeorological models increases confidence that the correct deductions are being made. In several instances the spectral data appear to be a meaningful way to quantify stresses—through their effects on the canopies the crops achieve. As a consequence of the constancy of the harvest index of wheat and environmental constraints on the canopies achieved over most of the Wheat Belt, grain yield of wheat relates well to spectral vegetation indices during the period late stem extension to early grain filling. Collectively these findings help determine whether or not agrometeorological model estimates of plant canopy characteristics, that in turn, affect the model's photosynthesis, evapotranspiration, stress response, and yield subroutines, are being correctly predicted for particular production areas. The understanding of plant canopies represented by these advances have been incorporated into the subjective operational yield predictions of the Foreign Agricultural Service (FAS) of the USDA, while agrometeorological models that would use spectral inputs are still being revised.

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