Proceedings of the Crop Modeling Workshop, Columbia, Missouri, October 3-5, 1977
United States Department of Commerce, National Oceanic and Atmospheric Administration
Environmental Data and Information Service, Center for Environmental Assessment Services

YRB 77-07

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THE FUTURE ROLE OF A CROP MODEL IN LARGE AREA YIELD ESTIMATING[1]

Misnamed

A grain Sorghum Simulation Model And it's Application to forecasting crop growth And yield would be a better title.

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THE FUTURE ROLE OF A CROP MODEL IN LARGE AREA YIELD ESTIMATING

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Crop growth simulation models that consider the soil-plant-atmosphere continuum have only recently been introduced as research tools. The incentive to develop such models resulted from the successful modeling of photosynthesis toward the end of the 1960's. Crop growth simulation models for corn, cotton, alfalfa, short-grass, barley, and wheat followed in the early 1970's (Table 1). As illustrated, crop growth modeling is in its infancy. Crop growth models are primarily research tools; few, if any, are being used in management decision making. However, accurate crop growth modeling and yield forecasting could enable improved management decisions. Preplant and crop season weather and growing conditions can be useful in determining optimum planting date, matching crop to land productivity, optimizing fertilizer application rates, scheduling irrigations, planning insect control programs, and estimating harvest date and crop storage and handling requirements, both nationally and internationally.

Crop growth models may be useful to economists in cost benefit analyses. Growth models permit parametric analysis of cost returns on the production inputs of various management alternatives. Definition of genetic characteristics of particular crops may enable plant breeders to use crop growth models to estimate growth and production of various genetic materials for different climatic and physiographic conditions and select materials suited to a specific locale. The potential use of these models as management and research tools stimulated building the

Table 1. Plant or Crop Simulation Models in the Literature[3/]

CROP	AUTHOR(S)	YEAR
Alfalfa	Miles, Bula, Holt, Schreiber, et al.	1973
	Holt, Bula, Miles, Schreiber, et al.	1975
Barley	Kallis and Tooming	1974
Corn	Splinter	1973, 1974
	Russo and Knapp	1975
	Baker and Horrocks	1976
	Lemon, Stewart, and Shawcroft	1971
Cotton	Baker, Hesketh, and Duncan	1972
	Stapleton, Buxton, Watson, Molting, et al.	1973
	McKinion, Jones, and Hesketh	1975
Shortgrass prairie	Connor, Brown, and Trlica	1974
Sorghum	Arkin, Vanderlip, and Ritchie	1976
	Vanderlip and Arkin	1976
Soybeans	Curry, Baker, and Streeter	1975
Sugar beets	Fick	1971
	Fick, Loomis, and Williams	1975
Wheat	Rickman, Ramig, and Allmaras	1975
	Chin Choy, Jose, and Stone	1975
	Colwell and Suits	1975
	EarthSat	1976

[3/] W. W. Hildreth, Lockheed Elec., Tech. Memo.

grain sorghum crop growth simulation model.

Grain sorghum is exceeded only by wheat, rice, corn and barley in acreage of world crops. It is grown on all six continents in regions where the average summer temperature exceeds 20°C and the frost-free season is 125 days or more. Because grain sorghum can tolerate either arid or wet climates, enabling production on marginal lands, its importance as a food and feed source is growing annually. Increased worldwide annual grain sorghum production and grain yields can also be attributed to the development of higher yielding varieties with insect and disease resistance, and to improved management practices.

Grain sorghum, like corn and other grain crops, is determinate and produces a genetically predetermined number of leaves on a given tiller. Grain sorghum has a C_4-dicarboxylic acid pathway of photosynthesis which is believed to be an adaptation for efficient, rapid carbon fixation in environments where water limits plant growth. Although usually grown as an annual, sorghum will grow replacement tillers if the primary tiller is removed. Thus, certain cultivars have multiple uses for grain and forage. Grain sorghum growth characteristics differ little over large regional areas, as a result of the relative insensitivity to photoperiod and the narrow genetic base among many varieties within a particular maturity class. These attributes simplify modeling sorghum growth and should enable the grain sorghum model described herein to be used over large areas with little alteration.

THE MODEL

Daily growth and development of an average grain sorghum plant in a typical field stand was calculated with this model. The appearance of leaves, their growth rate, and the timing of these events are growth characteristics simulated in the model. Light interception, photosynthesis, respiration and water use were modeled independently and used as submodels in the growth model. Daily dry matter accumulation is partitioned to the appropriate plant organs, depending on the stage of plant development. The cumulative dry weight for a crop is the product of the plant population and the weight of the modeled "average" plant. Likewise, crop yield is the product of the plant population and the weight of the modeled average plant grain weight. Most of the equations describing these processes are empirically derived from field measurements.

Input data required for the sorghum growth simulation model are given in Table 2. The model operates on a daily basis, and therefore only daily climatic inputs are required. Other inputs are initialized at the outset of the modeling run. A generalized flow diagram is given in Figure 1. Where is This?

SEEDLING EMERGENCE

Seeds will imbibe water at very low soil water contents. Therefore calculated seedling emergence depends primarily on temperature. Mean air temperature is used to compute days to emergence. The threshold soil temperature, below which seedlings will not emerge, is approximately 10°C. Above this threshold sorghum seedlings will emerge when a predetermined number of heat units have accumulated, depending on sowing depth.

Table 2. Input data required for sorghum growth simulation model.

Plant data

- Leaf number -- total number of leaves produced
- Leaf area -- maximum area of each individual leaf, cm^2

Planting data

- Planting date
- Plant population
- Row width
- Row direction

Climatic data (daily from planting to maturity)

- Maximum temperature, C
- Minimum temperature, C
- Solar radiation, langleys per day
- Rainfall, cm

Location data

- Extractable soil water capacity, cm
- Initial extractable soil water content, cm
- Latitude

canopy is computed by using a modification of the Bouger-Lambert equatio (commonly referred to as Beer's Law).

POTENTIAL NET PHOTOSYNTHESIS

Potential net photosynthesis, defined as the net CO_2 fixed during the daylight hours on a ground area basis for nonlimiting water and temperature conditions, is calculated using relationships developed from data obtained from a canopy gas exchange chamber and simultaneous light interception measurements.

EVAPOTRANSPIRATION

Potential evapotranspiration is calculated using a relationship between net radiation, saturation vapor pressure, and relative humidity. Potential evapotranspiration, E_o, is computed as:

$$E_o = 1.28\ \mathrm{DELTA}/H_o\ (\mathrm{DELTA} + \mathrm{GAMMA})$$

where DELTA = slope of the saturation vapor pressure curve at mean air temperature, GAMMA = constant of wet and dry bulb psychrometer equation, and H_o = net radiation, cm H_2O (evaporation).

Evapotranspiration is calculated as the sum of transpiration and soil evaporation. Transpiration, E_p, is dependent upon LAI and is computed as:

$$E_p = 0.53\ E_o\ (\mathrm{LAI})^{1/2} \quad \text{for LAI} < 3$$

except when soil moisture is limiting. Potential soil evaporation, E_{os}, is calculated by:

$$E_{os} = E_o \quad \text{if LAI} < 0.5$$

or

$$E_{os} = (D * H_{os}) / (D + T) \quad \text{if LAI} \geq 0.5$$

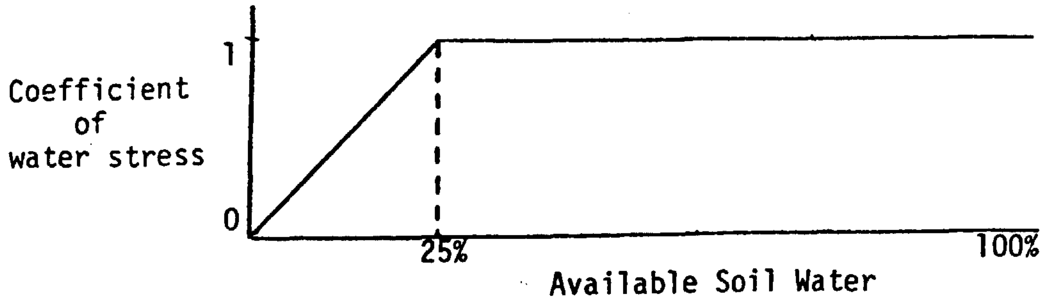
where D = DELTA/GAMMA and H_{os} = net radiation at soil surface. Soil evaporation is calculated from the potential and is dependent upon the condition of the soil (soil moisture and stage of drying).

WATER AND TEMPERATURE STRESS

A series of efficiency functions which reflect the effects of non-optimum ambient temperature and soil water conditions on plant growth are used in the model. Each efficiency parameter is a dimensionless coefficient with a value from 0 to 1.

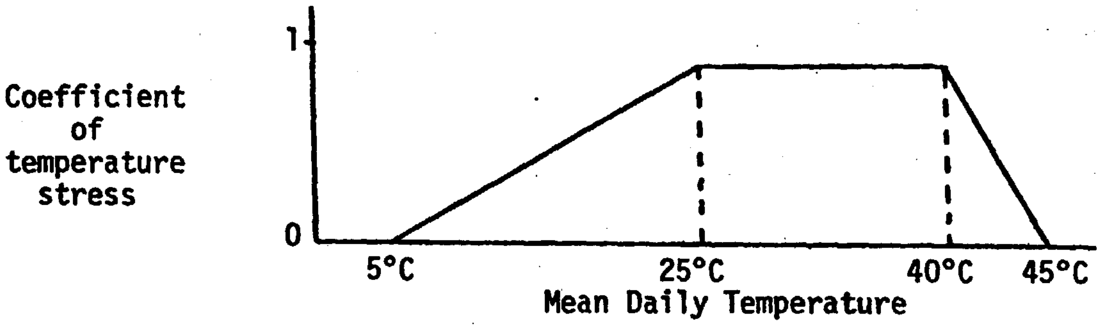
The soil moisture level at which transpiration is reduced depends on LAI and soil-water holding capacity. If extractable soil water falls below this level, the coefficient of water stress becomes less than 1. The water stress coefficient, Figure 2, is used to reduce transpiration and net photosynthesis.

Figure 2



Mean daily ambient temperature is used to approximate the crop temperature. Extremes of temperature constrain the photosynthetic rate. A temperature stress coefficient, Figure 3, is used to reduce net photosynthesis.

Figure 3



NET PHOTOSYNTHESIS

Net photosynthesis is computed by multiplying potential photosynthesis by the coefficients of water and temperature stress, and then subtracting nighttime respiration losses. This expression for net photosynthesis is based on the hypothesis that limiting water and temperature conditions proportionately reduce photosynthetic rate regardless of other limiting variables. Reductions in net photosynthesis, because of unavailability of soil moisture, were considered to be proportionate to the reduction in plant evaporation resulting from limited water availability. The effect of plant temperature extremes is based on an optimal temperature range between 25 and 40°C, and photosynthesis completely inactive below 5 and above 45°C.

DRY MATTER

Net photosynthesis computed as just described is converted to dry matter using the following relationship:

$$DM = \frac{12}{44} \times \frac{1}{0.4} \times p$$

where DM is dry matter, 12/44 is the ratio of molecular weights of C and CO_2 respectively, 0.4 is the proportion of the plant dry matter that is carbon, and p is net photosynthesis.

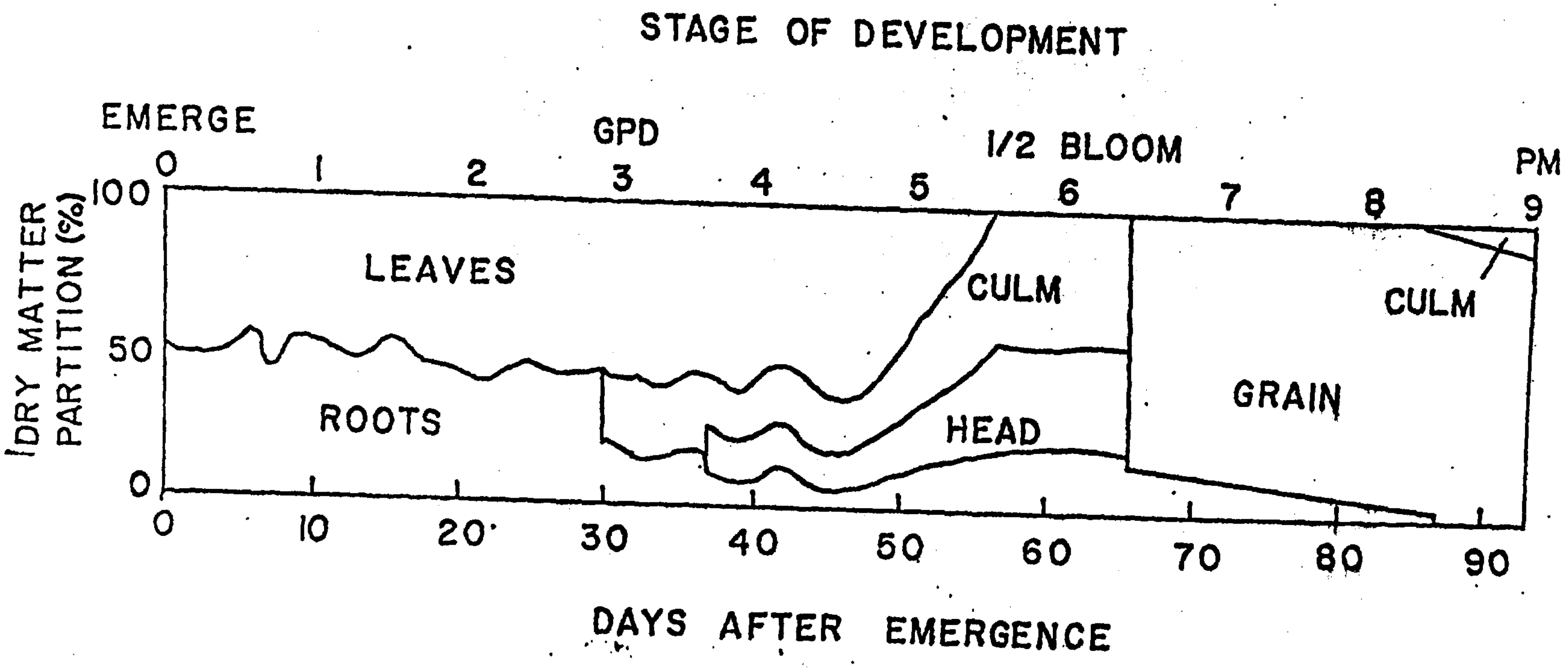
PHASIC DEVELOPMENT

Three stages are particularly important in determining what plant parts are increasing in weight: growing point differentiation (GPD), half bloom (HB), and physiological maturity (PM). Because leaf appearance and expansion were simulated in the grain sorghum model, phasic development was defined with respect to the appearance of leaves. For example, GPD normally occurs about midway between five leaves fully expanded and flag leaf visible in the whorl. The date GPD occurs was defined as the midpoint between the computed date that leaf 5 (counting from the base) reaches maximum area and the computed date that the flag leaf emerges.

DRY MATTER PARTITIONING

Dry matter is empirically partitioned to the appropriate plant parts, depending upon the development of the plant (Fig. 4). For example, the plant makes much of its vegetative growth during the period from GPD to HB. Early in that period dry matter is partitioned to leaves, roots and culm. Leaves have first priority; the amount of dry matter production

Figure 4


STAGE OF DEVELOPMENT
EMERGE
GPD
1/2 BLOOM
PM
0
1
2
3
4
5
6
7
8
9
DRY MATTER PARTITION (%)
100
50
0
LEAVES
ROOTS
CULM
HEAD
GRAIN
CULM
0
10
20
30
40
50
60
70
80
90
DAYS AFTER EMERGENCE

is partitioned to roots and culm in a 0.4:0.6 ratio, with at least 20% of the daily dry matter production going to the roots. During the remaining time until half bloom, dry matter is partitioned to leaves, roots, culm and head. Leaves again have first priority. Remaining daily dry matter production is partitioned to the roots, culm and head in the proportions 0.20:0.45:0.35, respectively.

MODEL LIMITATIONS

Several aspects need further consideration. Timing of stages of development and partitioning of dry weight to plant parts need to be made more responsive to soil water and nutrients available to the active plant roots. Both water and nitrogen stress can affect the rate of leaf appearance, maturity, leaf senescence, and leaf area. Development of these relationships for field-grown plants would result in improved timing and partitioning simulations. Including nitrogen nutrition in the model would allow its use as a management factor in modeling and would enable protein content of the grain to be computed. Quantitative relationships among limited available soil water and internode elongation, floral abortion, and uppernode branching are important in realistically modeling sorghum crop growth. These morphological aspects, although not considered here, can have an immense impact under certain conditions and will need to be dealt with in the future. For the model to operate correctly over a wide range of plant populations, tillering must be accounted for. To adequately simulate yield, two major components of yield must be modeled -- seed number and the rate of grain filling.

FORECASTING CROP GROWTH AND YIELD

In general, regression models are being used to forecast yields. Between-year regression models assume that the current year is part of a composite population, as were the base period years which provide expressions of yield as a function of meteorological variables. These between-year models require historical yield and weather data to develop the regression equations. Within-year crop yield models, like the one to be discussed, have the advantage of providing crop yield forecasts without the dependence on a base period. Because of limited weather and yield data, a between-year model requires a minimum of five years of data collection before it can be implemented. The necessary data are often lacking for specific locales. The within-year model permits crop development and yields to be projected from any point in the growing season by using weather probability data. The weather probabilities are developed from historical weather records for many crop seasons. Such data can describe the probability of specific weather events (i.e., 1, 5, 10 consecutive rainless days anytime during the growing season).

In one study, crop growth and yield were simulated for 20 years for six different levels of available soil water at the start of each growing season; i.e., 120 seasons of simulated grain sorghum growth and yield data were then available for use in the stochastic approach to yield forecasting. The simulated data were used to develop a conditional probability forecasting technique. Cumulative distribution functions (CDF's) conditioned on leaf area and available soil water were developed with the simulated crop growth data for Temple, Texas, for five dates during a growing season (0, 30, 45, 60 and 75 days after emergence (DAE)). These CDF's were then used to forecast grain sorghum yields for a typical grain sorghum crop in Temple, Texas, during the 1974 growing season.

The climatological forecast sequence is presented in Table 3. The first forecast was made at 0 DAE for LA of 0 cm^2 and ASW (available soil water) > 9.0 cm. LA and ASW values were obtained from the model simulation data for 1974. From the CDF's the probability was 60% that the yield would lie between 4600 and 7800 kg/ha. Similarly, mean yield and the 60% probability yield range were forecast on the selected dates throughout the growing season through 75 DAE, when the forecasted mean value was 4392 kg/ha and the yield modeled using only the 1974 growing season weather was 3822 kg/ha. Data in Table 3 illustrate that the variance around the mean remained about the same for each forecast. However, the yield associated with the 20 and 80% cumulative probability and the mean value drew closer to more realistic values as the season progressed until, at 75 DAE, the forecasted mean yield was essentially the same as the measured yield (4398 kg/ha).

Because stages of development, plant organ weights including head weight, and leaf number are calculated within the growth simulation model, it should be possible to measure these values in the field and use them in making a forecast. As the crop develops, new feedback data measured in the field or measured via satellite and aircraft overflight would be used in forecasts. With this method, the model could be started at any time in the growing season, with measured data describing the state of the crop to that point. Using generated weather data for the remainder of the season, new yield probabilities can be calculated. This process continues as the season progresses, continually updating or adjusting the model with measured inputs and then calculating new yield probabilities which should be more accurate and have less variance than forecasts

Table 3

FORECASTED, MODELED AND MEASURED GRAIN SORGHUM[1] YIELD - 1974

TEMPLE, TEXAS

DAE	GROWTH STAGE[2]	LA (cm^2)	ASW (cm)	FORECASTED RANGE† ($kg\ ha^{-1}$)	FORECASTED MEAN ($kg\ ha^{-1}$)
0	--	0	>9.0	4600-7800	6214
30	3 (GPD)	>440	>9.0	3400-7250	5580
45	4-5	>1750	>9.0	3700-7200	5441
60	6 (HB)	>2650	≤10.0	2700-6100	4406
75	7-8	>2490	≤9.0	2800-6000	4392
97	9 (PM)	MEASURED YIELD		4398	
97	9 (PM)	MODELED YIELD		3822	

[1] Variety - Big Yellow - McGregor Seed Co.

[2] After Vanderlip (GPD - Growing Point Differentiation, HB - Half Bloom, PM - Physiological Maturity)

† 60% Probability

made earlier in the season. This approach enables forecasts in a real-time framework useful for real-time decision-making information for the farmer or other user groups.

The feedback submodel for the growth simulation model was just recently developed. A weather model that can be used to generate probable weather during the growing season will be used with the grain sorghum model to compute realistic yield probabilities.

A sample of the use of the feedback submodel is given in Table 4. At four dates, ground truth measurements were used to update the model for grain sorghum growth simulation from the date of the feedback entry to physiological maturity.

On June 7, for example, the following ground truth information was fed back to the model: 14 leaves full grown, LAI = 2, plant dry weight = 20.05 grams, head dry weight = 3.69 grams. The model then accurately simulated both the total plant dry weight and the head dry weight and computed the date of physiological maturity within three days of the observed event. This forecast was made one month before physiological maturity and approximately two months before harvest. LAI was always overestimated because the senescence submodel of the grain sorghum simulation model is not responsive to limited soil water conditions.

THE HYBRID SPECTRAL-PHYSIOLOGICAL MODEL

The hybrid model combines the sorghum simulation model with spectral models that use LANDSAT multispectral scanner (MSS) data or a combination of LANDSAT and weather data for estimating plant growth parameters for updating and adjusting model computations.

One of the major inputs and outputs of the sorghum simulation model

TABLE 4

BAKER FIELD 1
TEMPLE, TEXAS
1976

	GROUND TRUTH	NO FEEDBACK	FEEDBACK			
			5-3	5-18	6-7	6-24
5-3						
# LEAVES FULL	8	14	8*			
LAI	0.83	3.35	0.83*			
PLANT DRY WT (GM)	2.36	16.16	2.36*			
HEAD DRY WT (GM)	0.00	2.22	0.00*			
5-18						
# LEAVES FULL	10	14	14	10*		
LAI	1.51	3.16	3.32	1.51*		
PLANT DRY WT	6.03	29.94	14.13	6.03*		
HEAD DRY WT	0.00	7.05	1.57	0.00*		
6-7						
# LEAVES FULL	14	↓	14	14	14*	
LAI	2.00		3.05	3.15	2.00*	
PLANT DRY WT	20.05		37.10	20.41	20.05*	
HEAD DRY WT	3.69		8.72	6.30	3.69*	
6-24						
LAI	2.40		2.06	2.94	2.59	2.40*
PLANT DRY WT	44.92		57.01	46.54	46.44	44.92*
HEAD DRY WT	21.27		31.01	12.17	17.25	21.27
PHYS. MATURITY						
DAY	7-13	6-3	7-4	7-20	7-10	7-10
LAI	1.40	2.95	2.75	2.65	2.43	2.25
PLANT DRY WT	50.70	50.05	66.52	69.40	50.04	56.99
HEAD DRY WT	35.70	31.93	43.92	44.34	33.05	35.00
EMERGENCE	3-15	3-11	3-15*	3-15*	3-15*	3-15*
ANTHESIS	6-7	5-10	6-2	6-14	6-7*	6-7*

* Feedback inputs

is leaf area. Experience has shown that leaf area can be estimated from satellite data. This information could be used as feedback to upgrade the simulation model's prediction of crop condition or to override or reinitialize the simulation model.

Another important aspect of this simulation model is the requirement for plant population input. If populations change for any reason during the growing season (disease, hail, etc.), this information needs to be updated in the model. Satellite data are a measure of characteristics associated with plant population and could provide adjustments that would improve the accuracy of the simulation model yield forecasts. Although the satellite data are not a measure of plant population per se, they respond to green biomass variation due to stand and to green leaf area. The spectral data characterize fields with information that is a surrogate for plant population. Satellite-obtained estimates of LAI are most useful for extending the simulation model to large geographical areas and for documenting field-to-field variability. Ground verification or feedback data for all fields in a state might be prohibitively expensive.

The sorghum simulation model contains a soil water balance subroutine. Plant-stress status is determined from available soil water in the profile, which is computed daily. With this information plus information on physiological development of the crop and yield probabilities, information useful for on-farm management decision making can be disseminated. These farm management advisories might range from selection of appropriate plant populations or optimal planting date to the best time to irrigate or the amount of water to use for irrigation.

The spectral relationships can help to identify whether optimum seeding rates are being used, to identify plant growth stresses, to stratify production areas into subareas of similar soil type and farming practices, to provide synoptic indications of available soil moisture when such data are not available from ground measurements, and to document vegetation cover as it relates to soil erodibility by wind or water.

The interdependency of the two models and their combined output is illustrated in Table 5. Management decisions based on the output are also listed.

High correlations between spectral data and plant growth parameters have been obtained (Table 6). These high correlations between LANDSAT-derived vegetation indices or direct digital data from LANDSAT indicate that spectral data could be used to estimate plant condition parameters in individual fields over large areas for feedback into the sorghum plant growth model. Use of the simulation model, weather probabilities, and the spectral data in a complementary manner should result in improved knowledge of crop growing conditions and resultant yield.

EXTENDING THE SINGLE-PLANT, SINGLE-FIELD MODEL TO LARGE AREA FORECASTS

By simulating single-field growth and development in an adequate sample of representative fields in a large area, one should be able to estimate plant growth and development in that area. The number of fields (grid density) required for adequate coverage is critical. Model input data requirements for simulation of growth and development at each field would not normally be available and would have to be extrapolated from the existing meteorological network data. The impact that extrapolated input data may have has yet to be assessed.

Table 5. Simulation and Spectral Model Limitations, Outputs and Decision Options.

CROP DEVELOPMENT STAGE	YIELD LIMITING FACTORS	SPECTRAL MODEL OUTPUT	SIMULATION MODEL OUTPUT	MANAGEMENT DECISIONS
Preplant	Available water	Surface temperature as an indication of adequacy for germination; moisture conditions	Initial inputs: planting configuration plant population initial moisture	Irrigate or not Fertilizer application Seeding rate Alternative crops Seeding date selection Tillage Herbicide use
Planting	Available water	Bkgrd. (soil) Drainage Topography Variability		Variety Seeding rate
Emergence	Available water N available Leaf area index Avg. weather to end of season Avg. weather to end of stage Crop status	Planted (tilled) vs non-tilled acreage	Date of emergence Available soil water Growth: leaf appearance, leaf expansion Dry matter: CO_2, R_s Partitioning: leaf, stem, roots	Irrigation scheduling Sidedressing of fertilizer
Growing Point Differentiation (GPD)	Available water N available Leaf area index Avg. weather to end of season Avg. weather to end of stage Crop status	Vigor (synoptic) Leaf area index Crop cover Green biomass Crop I.D. and hectarage estimate updates	Available soil water Growth: leaf appearance, leaf expansion Dry matter: CO_2, R_s Partitioning: leaf, stem roots, head Date of GPD	Irrigation scheduling Sidedressing of fertilizer
Half-bloom (HB)	Available water N available Leaf area index Avg. weather to end of season Avg. weather to end of stage Crop status	Vigor (synoptic) Leaf area index Crop cover Green biomass Crop I.D. and hectarage estimate updates	Available soil water Dry matter: CO_2, R_s Partitioning: leaf, stem, roots, heads Date of HB	Irrigation scheduling Harvest, transportation, storage needs preparations
Physiological maturity (PM)	Storms, disease, weathering of grain	Vigor (synoptic) Green leaf area duration or senescence rate Crop cover Discrimination between confuser crops	Growth: leaf appearance, leaf expansion Dry matter: CO_2, R_s Partitioning: leaf, stem, roots, head Date of PM	Harvest date Multiple cropping Post-harvest tillage Harvest, transportation, storage facilities

Table 6. Simple linear correlation coefficients between eight vegetation indices and ground truth and between individual LANDSAT digital count and ground truth for the pooled data for 5/3, 5/21, 6/8, and 6/26 from grain sorghum fields in Bell County, Texas in 1976 (n = 25) (table from reference 9).

LANDSAT Vegetation Indices[9/]	Ground Truth Information Leaf Area Index	 BIOMASS	 Plant Height	 Plant Cover
	Correlation Coefficients, r			
TVI	0.836**	0.744**	0.826**	0.717**
TVI 6	0.867**	0.778**	0.861**	0.763**
RVI	-0.824**	-0.722**	-0.817**	-0.707**
PVI	0.892**	0.792**	0.877**	0.786**
PVI 6	0.916**	0.806**	0.907**	0.830**
DVI	0.893**	0.791**	0.877**	0.785**
SBI	-0.441*	-0.263	-0.459*	-0.470*
GVI	0.893**	0.800**	0.881**	0.795**

LANDSAT MSS Bands	Ground Truth Information LAI	 BIOMASS	 Plant Height	 Plant Cover
MSS4	0.036	-0.142	0.061	0.130
MSS5	-0.389	-0.447	-0.365	-0.288
MSS6	0.795**	0.641**	0.799**	0.759**
MSS7	0.839**	0.690**	0.837**	0.770**

* Statistically significant at the 0.05 probability level.

** Statistically significant at the 0.01 probability level.

[9/] Refer to transformed vegetation index, ratio vegetation index, perpendicular vegetation index, difference vegetation index, soil brightness index, and green vegetation index, respectively; for details see references 8 and 9.

INPUT DATA

It may be necessary to supplement satellite data with lower altitude aircraft imagery for areas where clouds eliminate most or all of the satellite coverages during the growing season. However, the areal coverage limitations of aircraft and the difficulties in scheduling them for low cloudiness days are enormous and restrict their use in wide-area coverage.

The predictability of the satellite coverage schedule months in advance, once it is successfully in orbit, has advantages in efficiently deploying ground resources in operational systems. Data are collected with the satellite system for the same time of day at each ground location and with the same sensor system worldwide. Uniformity of the data sets produced by this system simplify the data processing.

Aircraft scanners are available with a larger number of spectral bands than are available on spacecraft systems. The Thematic Mapper onboard the LANDSAT follow-on missions will help eliminate this disparity. Since aircraft are much closer to the earth than orbiting satellites, the data are of much higher resolution. If it is important to identify plantings as small as 1 hectare, then with current technology aircraft data must be used. But much of the production from such small plantings is consumed in subsistence economies; high-quality synoptic images that indicate the general growing conditions may be sufficient to indicate production in such areas.

The inputs from satellite and aircraft systems are about the same -- digital magnetic tapes and color or black-and-white images. Their data processing and the interpretation procedures are similar. Factors dictating a choice depend on areal extent of the application, cloud conditions, resolution requirement, and data system operational costs per unit area.

The amounts and kinds of ground truth information needed for large area yield predictions are constantly evolving. This is because ground truth needs are interdependent with advances in data processing, image enhancement and interpretation techniques, quality of crop calendars, amount of ancillary information (soil types, rainfall) available and its use, the precision with which it is known how the plant reacts to environmental stresses -- i.e., physiological meaningful growth models, experience, interpretation keys, and other memory features. The ground truth needed today may be quite different from that required next year or 5 years from now, depending on advances in other areas.

Ground truth requirements are becoming more elaborate, but not necessarily to improve crop identification or estimate acreage planted. Rather, the impetus is to better document soil conditions and plant canopy characteristics for plant simulation and bidirectional reflectance models.

Ground truth can be obtained for domestic situations. It is another matter to obtain ground truth for other countries. Johannsen, Baumgardner, and Wiegand (unpublished manuscript for 1972 Annual Agronomy Meetings, Miami, Florida) pointed out that agronomists, geographers, and hydrologists use their knowledge of the relation between spectral changes and known changes to obtain specific information about areas where no ground truth was taken. Thus, the experience of the users is an important factor in defining ground truth requirements.

The mix of soil background and vegetation information in the spectra for crops, rangeland, and forest scenes has hampered extraction of the vegetation information per se. Criteria have been developed for distinguishing vegetation from the soil background. It has been shown that the LANDSAT data space can be partitioned into zones corresponding to water, cloud shadow, low-reflecting soil, medium-reflecting soil, high-reflecting soil, clouds, low vigor vegetation, medium vigor vegetation and high vigor vegetation without any a priori knowledge of specific ground conditions for a scene. Such interpretations will proliferate as the universality of the spectral characteristics of water, vegetation, soil, clouds, and cloud shadows, on which the approach is based, is tested and proved. As the spectral categories for soil and vegetation are calibrated against ground conditions (or as the ground conditions are calibrated against their spectra?), the need for ground truth may lessen.

CONCLUSION

A model that simulates the response of plants to the soil and aerial environment (physiological crop weather model) can be used in combination with spectral models that document the integrated plant response to improve crop yield forecasts for large areas. The physiological model operates on a daily basis. Modeled dry matter accumulation each day is apportioned to the appropriate plant organs. The spectral data provide feedback to the physiological model in terms of LAI or green biomass, and aid considerably in explaining field variations in stand and current or previous differences in management that affect plant vigor or soil productivity.

The hybrid model approach will improve as the influences of weather and plant stress on phasic development and yield components (seed number seed size, and number of heads per unit land area) are better quantified

REFERENCES

1. Arkin, G. F., C. W. Richardson and S. J. Maas. Forecasting grain sorghum yields using probability functions. Submitted to Trans. ASAE for publication.

2. Arkin, G. F., J. T. Ritchie and S. J. Maas. A model for calculating light interception by a grain sorghum canopy. In Press. Trans. ASAE.

3. Arkin, G. F., R. L. Vanderlip and J. T. Ritchie. 1976. A dynamic grain sorghum growth model. Trans ASAE 19(4): 622-626, 630.

4. Crank, Keith. 1977. Simulating daily weather variables. Statistical Reporting Service, U.S. Department of Agriculture, Washington, D.C. 17 pp.

5. Crop Spectra Workshop. Sterling, Virginia. February 1-3, 1977. Compiled by Ecosystems International, Inc. (under contract NASW 3024), P. O. Box 225, Gambrills, Maryland 21054.

6. Kanemasu, E. T. and G. F. Arkin. 1974. Radiant energy and light environment of crops. Agric. Meteorol. 14: 211-225.

7. Monk, R. 1977. Characterization of grain sorghum emergence. M.S. Thesis. Texas A&M University, College Station, Texas.

8. Richardson, A. J. and C. L. Wiegand. 1977. Distinguishing vegetation from soil background information. Photogrammetric Engineering and Remote Sensing 43(12): 1541-1552.

9. Richardson, A. J. and C. L. Wiegand. 1977. Table look-up procedure for rapidly mapping vegetation cover and crop development. Symp. in Machine Processing of Remotely Sensed Data sponsored by LARS, Purdue University, Lafayette, Indiana. pp 284-297.

10. Richardson, A. J., C. L. Wiegand, G. F. Arkin, P. R. Nixon and A. H. Gerbermann. Spectral indicators of sorghum development and their implications for growth modeling. Submitted to Agric. Meteorol.

11. Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resources Research 8(5): 1204-1213.

12. Vanderlip, R. L. and G. F. Arkin. 1977. Simulating accumulation and distribution of dry matter in grain sorghum. Agron. J. 6: 917-923.