MODELING GROWTH, DEVELOPMENT, AND YIELD OF GRAIN LEGUMES USING SOYGRO, PNUTGRO, AND BEANGRO: A REVIEW

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ABSTRACT

The interactions between plants and their environment involve an elaborate collection of biological, physical, and chemical processes. To better understand the responses of crops to their environments, computer models are being used to study both the simple and complex aspects of this system.

INTRODUCTION

Models for analyzing agricultural production systems have evolved into practical tools for scientists, engineers, planners, managers, and growers, who are responsible for improving management and control of such systems. Crop production simulation models were first reported in the early 1970s (Bowen et al., 1973; Stapleton, 1970; de Wit and Goudriaan, 1974). Early promises of their value for assisting crop system researchers in planning research and making improved recommendations were not realized as rapidly as projected. There were several reasons for this. One major reason was that model developers did not foresee the time and effort required to make the model usable by others. Most were developed by one researcher or a small group of cooperators to run on mainframe computers. After several models were published and after microcomputers became widely available in the 1980s, model developers learned that major efforts were required in programming, documentation, and education to make the models useful to a wider audience than the developers themselves. A second reason for lack of wider acceptance and use of crop simulation models was that potential users were not confident of their range of validity and their limitations. Field research for testing the models has been an essential component of the evolution of this technology. This testing has provided feedback to the modeling groups, who as a result continued to improve their models, thus making previous models obsolete, and developed new applications for their models.

This pattern of model development, testing, improvement, and implementation for easy use by researchers has led to the evolution of highly useful tools. Experience by several groups has demonstrated the necessity for a continued effort to maintain and improve these models to meet the changing needs and expectations of users ranging from farmers to policy makers. The purpose of this article is to describe the evolution of the development of a group of grain legume models, their content, and their testing as an example of the sustained effort required for their continued development and acceptance. **KEYWORDS.** Computer model, Crop simulation, Carbon balance, Water balance, Vegetative development, Reproductive development, Yield production.

OBJECTIVE

The objective of this article is to give an overview of the current status of the grain legume models SOYGRO, PNUTGRO, and BEANGRO. These simulation models have been developed at the University of Florida for the following leguminous crops: soybean (*Glycine max* [L.] Merr.), peanut (*Arachis hypogea* L.), and dry bean or common bean (*Phaseolus vulgaris* L.). The models SOYGRO, PNUTGRO, and BEANGRO have essentially the same mathematical structure and data file format. They simulate the timing of vegetative and reproductive development stages and dry matter growth and yield as a function of different soil, weather, and crop management conditions. Crop-specific and cultivar-specific data files provide coefficients for simulating the responses of a particular crop and cultivar to the environment. The cultivar-specific coefficients quantify the thermal and photoperiod requirements for reproductive development of a cultivar, as well as vegetative and reproductive growth characteristics. Growth in each model is based on the carbon, water, and nitrogen balances of the plant. A one-dimensional soil water model simulates water availability to the root system. The models require daily weather data, soil water holding capacity, root development characteristics, and crop management information as inputs.

Tests of the models at various locations in the United States and other countries indicate that major differences in development and yield due to changes in weather conditions and water stress can be simulated when inputs are reliable. The models have been incorporated in the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project's Decision

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Support System for Agrotechnology Transfer (DSSAT), which includes a data base management system, crop simulation models, and application programs. The models have been distributed to a large group of researchers, extension personnel, consultants, and others, and are used in various levels of agricultural applications. This wide acceptance shows that there is a need for a continuous effort to maintain and improve the grain legume models and to develop new applications.

GENERAL

SOYGRO Version 5.42 (Jones et al., 1989), PNUTGRO Version 1.02 (Boote et al., 1989b), and BEANGRO Version 1.01 (Hoogenboom et al., 1991b) are process-oriented computer models which predict growth, development, and yield of soybean (*Glycine max* [L.] Merr.), peanut (*Arachis hypogea* L.), and dry bean or common bean (*Phaseolus vulgaris* L.), respectively. The models have been developed by an interdisciplinary research team at the University of Florida. The original model used as a base for the other models was SOYGRO Version 4.0, developed from 1980 to 1983 (Wilkerson, 1983a). It was coupled to the soil water balance model developed by Jones and Smajstrla (1980), and documented as SOYGRO Version 4.2. It was tested with 'Bragg' and 'Cobb' cultivars grown in Florida on a Millhopper fine sand (loamy, siliceous, hyperthermic Grossarenic Paleudults) under various irrigation regimes. The model was subsequently used to study the economic risks of irrigation management in Florida (Swaney et al., 1983; Boggess et al., 1983; and Boggess and Amerling, 1983). The soybean model SOYGRO Version 4.2 also served as the crop component in an integrated pest management model called Soybean Integrated Crop Management (SICM) model (Wilkerson et al., 1983b; Mishoe et al., 1984; Jones et al., 1986; Szmedra et al., 1987).

In 1983, a cooperative effort between the University of Florida team and the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project was initiated. A major goal of this work was to make the model more robust for use in other regions of the world where soils and climatic conditions differed from those in Florida. The first step of this process was to adapt a more general soil water model developed by Ritchie (1985). In addition, a preliminary phenology model developed by J. W. Mishoe (unpublished) which predicts development of vegetative and reproductive stages of soybean in response to photoperiod and temperature was included in the model. With these changes, a new version, SOYGRO Version 5.0, was documented and released (Wilkerson et al., 1985). In addition, a version was developed for application on personal computers, SOYGRO 5.0 - PC (Chang et al., 1985).

Over time, problems were discovered in applying SOYGRO Version 5.0 to diverse environments. A need was recognized to make a number of changes in the SOYGRO model to improve its performance over a range of soil, environment, climate, and crop management conditions. Concurrently, the IBSNAT project had defined standard input and output formats for climate, soil, and experimental data in an attempt to make all the models in the project more useful with minimal incompatibilities (IBSNAT, 1986). Again, the soybean model was revised to fit this standard format. In addition, several other improvements were made in the model to improve its performance over a range of soils and environments, which resulted in the most recent version of SOYGRO, Version 5.42 (Jones et al., 1989).

The development of PNUTGRO was guided by previous adaptations of SOYGRO Versions 4.2 and 5.0 to be able to simulate growth, development, and yield of peanut (Boote et al., 1983; 1985). Earlier versions of PNUTGRO have been published as Version 1.0 and 1.01 (Boote et al., 1987; 1988). The present PNUTGRO Version 1.02 was codeveloped with SOYGRO, Version 5.42 (Boote et al., 1989b). The development of BEANGRO was guided by previous adaptations of SOYGRO Versions 5.40, 5.41, and 5.42 (Jones et al., 1987; 1988; 1989) to be able to simulate growth, development, and yield of dry bean (Hoogenboom et al., 1989; 1991b). An earlier version of BEANGRO has been published as Version 1.00 (Hoogenboom et al., 1990c). An overview of the linkages between the models is shown in figure1.

SOYGRO Version 5.42, PNUTGRO Version 1.02, and BEANGRO Version 1.01 predict dry matter growth, leaf area index (LAI), crop development, and final yield of soybean, peanut, and dry bean, respectively, as a function of daily weather data for specific soil types. Soil parameters for each individual layer or horizon describe the ability of the soil to store water and to supply water to the

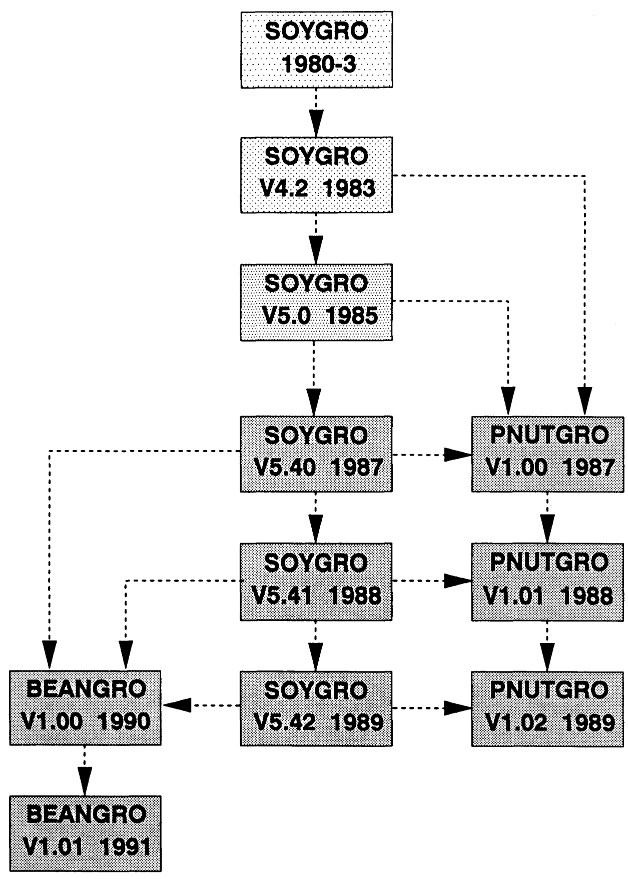

Figure 1–The history of the BEANGRO, PNUTGRO, and SOYGRO crop simulation models.

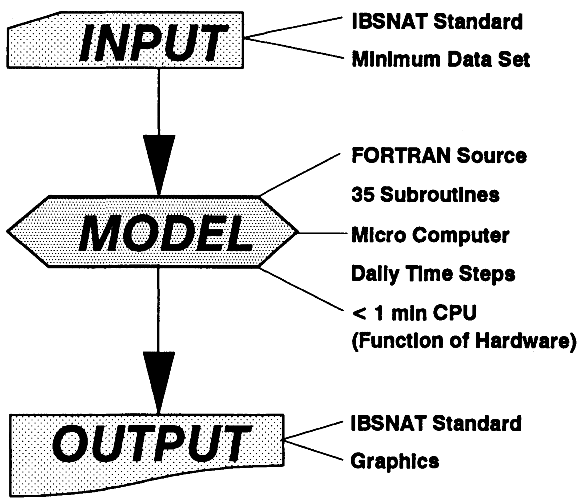

Figure 2–General characteristics, organization, and input/output structure of the BEANGRO, PNUTGRO, and SOYGRO crop simulation models.

roots. The models are also sensitive to cultivar selection, planting date, row and plant spacings, and irrigation management options. The general structure, organization, and input/output format of the models SOYGRO, PNUTGRO, and BEANGRO is shown in figure 2.

The current versions of the models are designed as research tools. Users can input their soil, weather, and management data as well as their measured crop growth data from experiments or from farmers' fields for testing or validating the models for their conditions. Experiments can be simulated with the model and compared in tabular and graphical forms with measured data. Scientists can conduct sensitivity analysis studies by interactively selecting combinations of soils, weather, cultivar, and management factors. And finally, users can use the models in risk analysis studies by simulating many cropping seasons over time and space by varying weather and soil inputs.

Pests and diseases are not included in the current models, although efforts with cooperators are under way to include leafspot damage and various types of pest damage on leaves, stems, roots, pods, and seeds. For peanut, a simulation of the progression of late leafspot (*Cercosporidium personatum* [Berk. and Curt] Deighton) on 'Florunner' peanut has been developed (Bourgeois, 1989). This model has been coupled to PNUTGRO Version 1.02 and predicts diseased leaf area, loss of leaf area, and disease severity. There are also other factors, particularly in the soil, that are not included in the models, such as various plant nutrients or calcium effects on fruiting. Therefore, results from the models should be viewed as potential yields under the specified regimes or weather and soil conditions.

Decision Support System for Agrothechnology Transfer

The legume crop simulation models have been integrated in the Decision Support System for Agrotechnology Transfer (DSSAT)(DSSAT can be purchased from the IBSNAT Project, Department of Agronomy and Soils Science, University of Hawaii, 2500 Dole Street, Krauss 22, Honolulu, HI 96822). The DSSAT is a microcomputer based shell which includes a Data Base Management System (DBMS), crop models, and application programs (IBSNAT, 1989; Jones, 1986; Jones et al., 1990). The DSSAT was developed as part of the IBSNAT Project through a grant with the U.S. Agency for International Development. Models for other crops within DSSAT include maize (Ritchie et al., 1989) and wheat (Godwin et al., 1989), and models for aroids (Prasad et al., 1991), barley (Singh et al., 1991), millet (Singh et al., 1991), potato (Griffin et al., 1991), rice (Jintrawet et al., 1991) and sorghum (Alargaswamy and Ritchie, 1991; Rao and Ritchie, 1991) are currently under development. All IBSNAT models include the same water balance model developed by Ritchie (1985), which uses the Priestley-Taylor equation (Priestley and Taylor, 1972) to estimate total daily potential evapotranspiration. The DSSAT was modified to be able to simulate and predict the effect of global climate change on crop yield, using the existing crop models within the DSSAT. All models use a similar Minimum Data Set (MDS), which defines the required input variables (IBSNAT, 1986, 1988, 1990a). This will allow for the exchange of data and files between models. For instance, a file which contains daily weather data for 1988 can be used as input file in either the soybean, maize, or other models. Also the soil profile characterization and description file can be exchanged between the various crop models.

Input and Output Data

Minimum Input Data

As part of the IBSNAT project, a set of data has been identified as minimum input requirements for the crop simulation models (IBSNAT, 1986, 1990a). The MDS is an attempt to reduce the number of variables which have to be collected by a collaborator, while at the same time allowing for the collection of enough data for proper model calibration and validation. To help collaborators and model users, procedures have been defined for data collection (IBSNAT, 1990b) and special forms have been published to record crop management, weather, and soil data (IBSNAT, 1988). In addition, the DBMS program is available to enter all data into the data base of DSSAT. The data entry programs conform to the data entry forms, so once all data have been manually recorded they can be directly entered into the computer. After data entry, a utility program will retrieve all field data and create ASCII input files for the models. An overview of the general data input requirements for the models is shown in Table 1.

The following files are defined as input files for the crop models: FILE1 for daily weather data; FILE2 for a chemical and physical description of the soil profile, with separate information for each horizon; FILE4 for initial organic matter in the soil at the beginning of the experiment; FILE5 for initial soil water content, nitrogen concentrations, e.g., NO_3 and NH_4, and pH for each horizon or layer of the soil profile; FILE6 for irrigation management, e.g., dates and amounts of irrigation; FILE7 for fertilizer management, e.g., dates, amounts and types of fertilizer; FILE8 for crop management, e.g., planting date, row and plant spacing and other information; FILE9 for

TABLE 1. Input variables required to run the BEANGRO, PNUTGRO, and SOYGRO crop simulation models

	Daily Weather Variables
	Solar radiation
	Precipitation
	Maximum air temperature
	Minimum air temperature
	Latitude (to calculate day length)
	Soil Variables
General	Runoff
	Soil albedo
	Permeability
	Drainage
	First stage soil evaporation
For each soil layer	Saturated soil water content
	Drained upper limit of extractable plant water (field capacity)
	Lower limit of extractable plant water (permanent wilting point)
	Initial soil water content
	Relative root distribution
	Crop Management Variables
	Planting date
	Plant density
	Row spacing
	Irrigation management (dates and amount)
	Cultivar selection
	Soil type
	Weather site

cultivar specific characteristics and genetic coefficients; and FILE0 for crop specific characteristics. The format of these files follows the standard definitions defined in IBSNAT Technical Report 5 (IBSNAT, 1990a).

Output Data

Field observed crop growth and development data are not required to be able to run the model. However, if a user wants to compare performance of the model with field data, a set of minimum experimental data has been defined similar to the one for model inputs (IBSNAT, 1988). Observed vegetative and reproductive development, yield and yield components, crop growth analysis, and soil water conditions can all be used as variables for comparison with simulated data. Output files to compare model predictions with field measured data include: FILEA for a summary of reproductive development and yield and yield components; FILEB for crop growth analysis; FILEC for weather conditions and soil water content of each horizon; FILED for plant and soil nitrogen; and FILEP for canopy photosynthesis, light interception, and other related factors. FILEB, FILEC, FILED, and FILEP contain variables which are all defined as a function of time or day of the year.

Weather

Daily recorded weather data are required inputs for the crop models. Weather data must be available beginning at the day of planting. If the simulation is initiated before planting, weather data are needed from the start of simulation. In this case the model can simulate the soil water balance before planting during field preparation when fertilizers and/or irrigation are applied. The following weather data are needed: daily total solar radiation; daily maximum air temperature; daily minimum temperature; and daily total precipitation. For many locations, only daily air temperature and precipitation measurements are available, in which case solar radiation has to be estimated before the crop models can be run. Solar radiation can be estimated as a function of sunshine hours or other weather variables by special programs and utilities which have been developed (Elizondo, 1992; Hook and McClendon, 1992).

Although the models require daily data as inputs, some of the variables are interpolated from daily values to calculate hourly values. For instance, hourly temperature is used for predicting vegetative and reproductive development. A new routine has been developed to predict hourly canopy photosynthesis as a function of canopy architecture and geometry and single leaf photosynthesis characteristics (Boote et al., 1990; Boote and Loomis, 1991). For this canopy-photosynthesis model, hourly radiation is needed to calculate hourly light interception and canopy photosynthesis rates. The calculation of hourly values, therefore, allows for a detailed description and simulation of some of the plant growth and development processes, while at the same time keeping the inputs relatively simple.

Soils

The crop models use a simple, one-dimensional soil-water balance model developed by Ritchie (1985). As a result, the required input variables are not as detailed as for the traditional soil physical models (Hillel, 1987). In the IBSNAT crop models the following information is needed for each soil horizon: lower limit of plant extractable soil water (LL) or permanent wilting point; drained upper limit (DUL) or field capacity; and saturated water content (SAT). The LL, DUL, and SAT for each horizon can be estimated from the percentage sand, silt, and clay, bulk density, and organic matter by a soil parameter program in the DSSAT (Ritchie et al., 1990). The classification and texture of a soil and the local slope are used to estimate the run-off curve numbers, based on the procedures developed by the Soil Conservation Service (1972). Soil color is used to estimate albedo, and a qualitative assessment of both drainage and permeability are used to estimate soil water flow through the profile. Other variables included as inputs are pH, aluminum saturation, and a relative rooting function. The soil water balance model was modified for the grain legume models to allow for a perched water table and upward flux of water under relatively wet soil conditions.

Management

Crop management information, which normally is available as part of an experiment or a field trial, is also needed as input to operate the models. These data include row and plant spacing; planting depth; planting date; start of simulation, which is the equivalent of the actual start of land and seedbed preparation; cultivar selection; and soil series or soil type. The soil type identifier is used as a cross reference to the earlier described soil profile characteristics, which are stored in a separate file. The individual characteristics of each cultivar are also stored in a separate file, discussed in another section of this article.

If a particular crop is irrigated, or if an irrigation experiment is simulated, the dates, amounts and efficiency of the irrigation applications are needed. Currently, the legume models are being modified in order to simulate the plant and soil nitrogen balance and to study responses to different types of nitrogen fertilizer management. For nitrogen management applications, both the types of fertilizer and times and depths of applications are needed.

It is critical that the models be properly and accurately initialized. Therefore, initial conditions at planting, which include soil water content, pH, NO_3^-, and NH_4^+ concentrations of each soil layer, are required. Available organic carbon and left-over residue material of both above- and below-ground plant material are needed as initial conditions if the nitrogen balance is simulated.

Although some of these measurements might look complicated for a first-time model user, they should already be available from many experiments, or they can easily be measured in experiments which are set-up for model calibration or validation. A model user needs to remember that the quality of model predictions depends very much on the quality of model inputs. If a user has all information available for weather, soils, and crops as described in this section, the legume models can be run. In addition, there are two other input files for the models. These two files normally do not have to be modified by a user and are described in the next section.

Cultivar Characteristics

In general, the vegetative development, reproductive development and growth processes of soybean, peanut, and dry bean are sensitive to both temperature and photoperiod. In most cases, each cultivar has unique photothermal requirements to achieve each of the developmental stages. Cultivar specific parameters are, therefore, used to define the sensitivity of each cultivar to day length or night length. In addition, threshold values for the most important phases are also defined; these include emergence, flowering, and physiological maturity. Reproductive parameters describe flower addition rate, pod addition rate, single seed and shell growth rate, and number of seeds per pod. Vegetative parameters describe leaf addition rate, average size of individual leaves, and leaf thickness (Hunt et al., 1990).

Although some of these parameters can be measured in the field, they are, in most cases, not recorded during regular experiments. Programs, therefore, have been developed to estimate these coefficients (Hunt et al., 1992). All three models have been released with parameters defined for several cultivars, mainly the one's for which experimental data were available. However, other cultivars exist or will be released by breeders which have never been used in crop simulation studies. For a correct estimation of the parameters of these cultivars, at least two or more studies will be required, with either different planting dates for the same location or the same planting date for different locations. In the user's guides of the models, an explanation is given of the procedures to estimate these parameters (Boote et al., 1989b; Jones et al., 1989). In one of the newer versions of the models, an option is available to interactively change the genetic coefficients (Hoogenboom et al., 1991b). The cultivar specific coefficients are summarized in Table 2.

TABLE 2. Cultivar characteristics and crop specific coefficients for the BEANGRO, PNUTGRO, and SOYGRO crop simulation models

Cultivar Characteristics
Photoperiod sensitivity
Temperature sensitivity
Accumulator thresholds
Pod growth rate
Number of seeds per pod
Flower addition rate
Pod addition rate
Leaf initiation rate
Leaf size
Crop Specific Coefficients
Photosynthesis
Growth respiration
Maintenance respiration
Temperature sensitivity
Biomass partitioning
Sensitivity to drough stress
Sensitivity to temperature stress
Leaf senescence
Percent protein (nitrogen) in vegetative tissue
Protein mobilization

Crop Specific Coefficients

In many models, numerical values for variables are mixed inside the computer code. This is inconvenient when one has to modify a number (coefficient), because one has to recompile and link all computer code. To avoid this problem, a special file (FILEO) has been defined in the grain legume models which defines all crop specific coefficients and functions (Table 2). These include both initial and final percentage protein in leaves, stems, roots, seeds, and shells; canopy light response curve; biomass partitioning to roots, leaves, and stems as a function of developmental stage; and temperature response curves for both vegetative and reproductive development, seed and shell growth, root growth, and photosynthesis. The major difference between the three models is found in the definition of the crop specific coefficients. Model users should not modify these crop coefficients, except for special circumstances.

Crop Processes (Functions)

The major components of the BEANGRO, PNUTGRO, and SOYGRO models are the vegetative and reproductive development, carbon balance, and water balance modules (fig. 3). In one of the most recent versions, a new nitrogen balance module is being developed for the SOYGRO model (Hoogenboom et al., 1990b), while in another version, canopy photosynthesis and light interception are being improved (Boote et al., 1990). The basic structure of the models, including the underlying differential equations, has been explained in several other publications (Wilkerson et al., 1983a; Boote et al., 1985; Hoogenboom et al., 1989).

Development

The models initiate the simulation of development as soon as planting has occurred. Each model predicts the

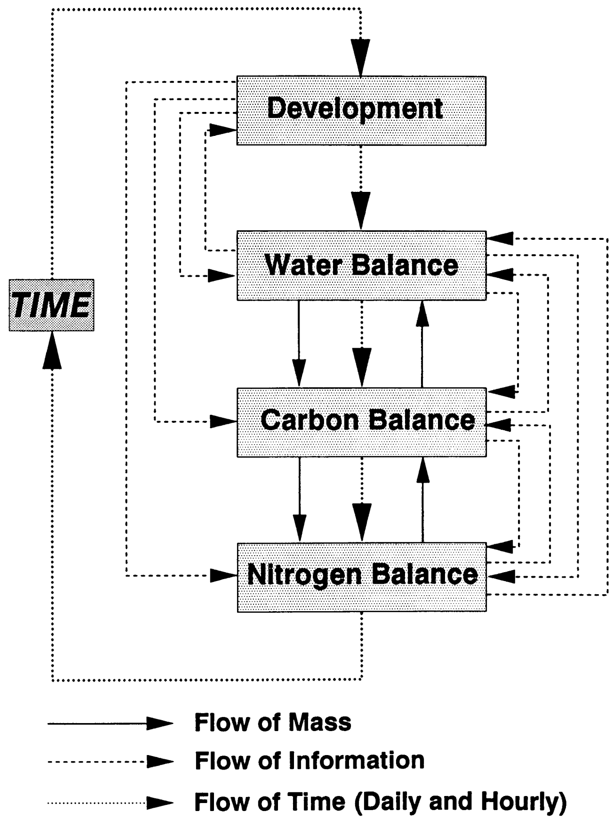

Figure 3–Relational diagram of the flow of mass and information between the most important modules of the BEANGRO, PNUTGRO, and SOYGRO crop simulation models.

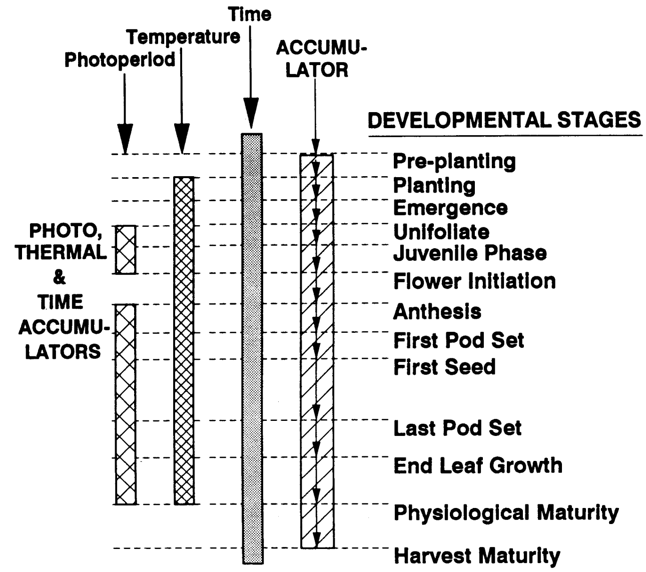

Figure 4–Vegetative and reproductive development, represented by the developmental stages, as a function of photoperiod and/or temperature, represented by the accumulator bars. (As shown here, the planting to unifoliate phase is a function of temperature and time only, while most of the other phases are a function of temperature, photoperiod, and time.)

germination period from planting to emergence; first full leaf expansion; a juvenile phase; flower initiation; start of flowering or anthesis; first pod occurrence; beginning of seed filling; end of leaf growth and expansion; end of pod growth and expansion; physiological maturity; and harvest maturity (fig. 4). The models also predict leaf development and vegetative node formation on the main stem. The latter has become more important with the introduction of light interception and photosynthesis as a function of row spacing, as this requires an accurate prediction of both plant height and width. Each of the reproductive stages mentioned earlier has a critical threshold value which is defined in the genetic coefficients. Each stage also has a specific photothermal accumulator which determines its sensitivity to temperature, photoperiod, and other environmental factors. For instance, the developmental phase for emergence is only dependent on temperature, while the number of days from the start of flowering to harvest maturity is controlled by both photoperiod and temperature. For most of the stage definitions in the peanut model only a temperature effect is included, while for soybean and dry bean it includes both photoperiod and temperature. A detailed description of modeling of soybean phenology can be found in Jones et al. (1991).

The temperature effect is based on a temperature response curve, rather than a degree day concept used in many other models. It is assumed that development will occur at an optimum or maximum relative rate of one for a certain optimum temperature range. If the temperature either decreases or increases above or below this range, the relative development rate will decrease, causing a delay in the overall development process. As a result, a certain event or phenological stage will occur at a later date (fig. 5).

Soybean, peanut, and dry bean are all short-day crops, but show various responses to day length within each species for different cultivars. The soybean cultivar 'Evans', which is grown at higher latitudes in the northern part of the United States, is almost insensitive to photoperiod, while the cultivar 'Jupiter', grown at lower latitudes in the tropics, is extremely sensitive. This sensitivity is defined in the model through two parameters. The first parameter defines the critical day length at which development begins to be delayed and the second parameter defines the degree of sensitivity to the change in day length beyond the critical short day. It is assumed that

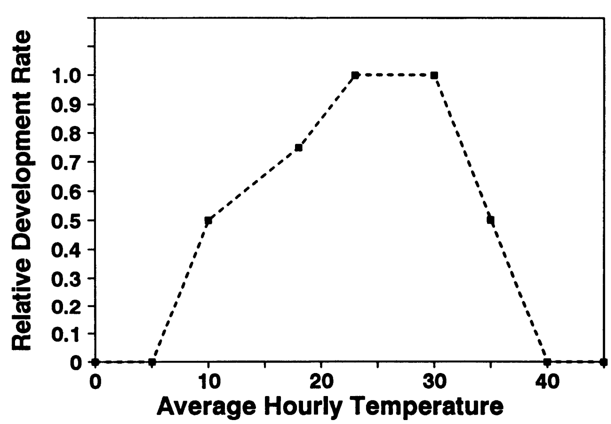

Figure 5–Relative reproductive development rate as a function of average hourly temperature (the response curve of an unpublished version of BEANGRO is shown).

under short day conditions development will occur at an optimum or maximum relative rate of one. Under long days this relative development rate can drop to zero, depending on the sensitivity of a cultivar to day length and actual length of the daily light period (fig. 6).

Carbon Balance

The models predict total canopy photosynthesis on a daily basis as a function of daily total photosynthetically active radiation, converted from daily total solar radiation. Variables which affect the daily total canopy photosynthesis rate are average daily temperature, leaf area index (LAI), nitrogen content of the leaves, specific leaf area (SLA), plant water deficit, and row and plant spacing. After daily total photosynthesis is calculated, it is reduced by the daily total maintenance respiration and by growth respiration, which accounts for the cost of conversion of assimilates to tissue dry matter. Partitioning to vegetative and reproductive structures is determined based upon the actual development phase. The highest overall priority in the models with respect to biomass partitioning is seed growth, followed by shell growth. For each day, potential growth of both seed and shell biomass is estimated, which is then compared with the actual amount of carbohydrates available from net daily photosynthesis. If demand is higher than supply, actual seed and shell growth is reduced proportionally. If potential reproductive growth is lower than available carbohydrates, the remainder of the carbohydrates not used for reproductive growth are partitioned to vegetative tissue for growth of leaves, stems, and roots. Vegetative partitioning and growth of vegetative components is a function of the vegetative or reproductive phase of the crop (fig. 7). Drought stress will also affect partitioning and increase the amount of carbohydrates distributed to the roots. The models calculate the amount of

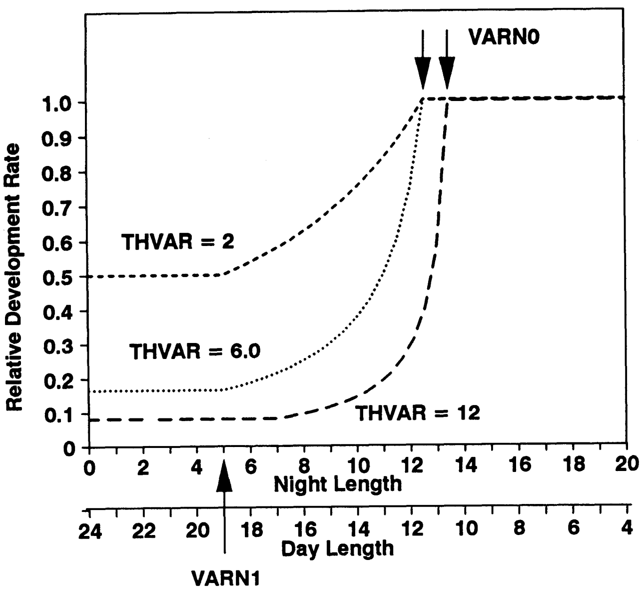

Figure 6–Relative reproductive development rate as a function of length of the daily light or dark period (THVAR = sensitivity of a cultivar to change in day length; VARN1 = critical short day above which a cultivar becomes sensitive to photoperiod; VARN0 = critical long day above which a cultivar's sensitivity does not change as day length increases).

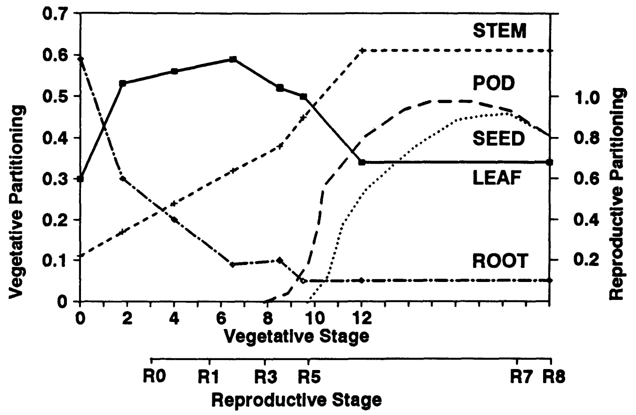

Figure 7–Relative biomass partitioning function to vegetative and reproductive components as a function of development (the response curve of an unpublished version of BEANGRO is shown). Vegetative partitioning (left y-axis), i.e., partitioning to stems, leaves, and roots, is a function of vegetative growth stage (top x-axis). Reproductive partitioning (right y-axis), i.e., partitioning to pods, seeds, and shells, is a function of reproductive growth stage (bottom x-axis).

carbohydrates required to convert photosynthates into new tissue and the fraction of protein, lipids, lignin, structural carbohydrates, organic acids, and minerals. They also compute the number of seeds and shells initiated on each day, and update the pod and seed weight, and number of seeds and pods of each cohort formed on each individual day. If the supply of carbohydrates is limiting, older cohorts have a higher priority than younger cohorts for growth of new reproductive tissue. Under certain stress conditions seeds and shells will abort.

The SLA of new leaf tissue is determined for each day and total new leaf area growth is calculated. The SLA of new leaf tissue is a function of the daily average temperature, daily radiation, and drought stress. The LAI is calculated based upon new leaf area growth and leaves abscised due to senescence. Leaf senescence is predicted as a function of age of the plant. Under drought stress, plants will abort additional leaves in proportion to the severity of the stress. During each time step, a certain amount of biomass is allocated for new root growth. Growth of new roots is distributed over the different soil layers as a function of the amount of existing roots, the amount of extractable water, and a root preference factor in each layer. Growth of new root tissue is converted to total new root length as a function of a root length-weight ratio. For each layer, root senescence is also predicted as a function of plant age and extractable water.

Water Balance

The water balance model has a one-dimensional soil model which predicts soil water flow and water uptake for each soil horizon or set of soil layers within a horizon (Jones and Ritchie, 1990). Each layer has a characteristic SAT, DUL, and LL. Water flow between layers is based on the following assumptions: if a layer has a water content higher than the DUL, saturated downward flow occurs proportional to the amount of additional soil water above the DUL level. If a layer has a water content between LL or DUL, unsaturated flow occurs proportional to the difference in soil water content between two adjacent soil layers and also taking into consideration the differences in soil properties between these two soil layers. Unsaturated flow can be either downward or upward. For layers which have a soil water content less than LL, no flow occurs. Water extraction by roots from each layer is calculated as a function of extractable soil water, root length density, and water uptake resistance.

In the lowest soil layer, drainage of excess water from the profile can occur. This water is permanently lost and will not be available for later extraction by the roots. There is also an option to include a water table by setting the saturated hydraulic conductivity to a very small value. The model does not include root death caused by a lack of oxygen due to a high soil water table. For the top surface layer, runoff can occur based on the total amount and intensity of rainfall and/or irrigation. A runoff coefficient is defined according to the standards set by the U.S. Soil Conservation Service (1972).

Evapotranspiration is estimated based upon procedures defined by Ritchie (1972). Potential evapotranspiration is calculated according to the Priestley-Taylor model (Priestley and Taylor, 1972). Inputs required for this model are daily maximum and minimum air temperature and daily total solar radiation (in energy units). Using these three inputs and soil albedo, this model has three different procedures to estimate daily total potential evapotranspiration, e.g., for $T_{max} < 5°$ C, $5°$ C $< T_{max} < 35°$ C, and $T_{max} > 35°$ C. Potential evapotranspiration is then partitioned to soil evaporation and transpiration as a function of canopy size, represented by total LAI. Soil evaporation is a function of the amount of energy which reaches the soil surface, which is directly proportional to the LAI, soil albedo, and the soil water content of the boundary surface layer. Root water uptake is a function of potential demand by the plant due to water lost by transpiration. If the roots are unable to extract the amount lost to transpiration because of either a high root resistance or a low soil water content in one or more soil layers, transpiration is reduced proportionally. If drought stress is observed by the plant, relative stress factors are introduced which reduce photosynthesis and expansive growth and increase biomass partitioning to the roots.

Nitrogen Balance

In all current versions of the legume models, it is assumed that nitrogen is non-limiting. Nitrogen can be supplied through either N uptake or N_2-fixation. The model does not consider the source of nitrogen, but does account for the cost of reducing N from NO_3^- to NH_4^+ and incorporating into proteins. The N_2-fixation is assumed to cost as much as NO_3^- reduction. Amino acids and proteins are formed at a fixed cost. The model calculates the fraction of protein in new tissue and includes the cost for growth respiration due to N assimilation and protein formation. Mobilization of nitrogen does not start until the beginning of reproductive growth; nitrogen can potentially be mobilized from the leaves, roots, stems, and shells to the seeds. This will cause a decrease in nitrogen content of vegetative tissue and senescence will occur, while at the same time more reproductive tissue can be formed. The reduction in leaf nitrogen, which induces leaf senescence, reduces the potential canopy photosynthetic rate, and therefore indirectly affects potential growth.

Verification, Calibration, and Validation

So far the most important functions and features of the GRO models have been described, which include the input formats and files, the structure and operation of the models, and the output formats and file (fig. 2; Tables 1 and 2). Ultimately, the outputs and predictions of the models are the most critical aspects of the models and are most visible to the user. To rely on the predictions of the models, one must verify, calibrate, and validate the models following initial development or modification (De Wit et al., 1978; Penning de Vries, 1977).

Verification

Verification relates to the description of the code with respect to the underlying processes of the model. Verification is done through a careful checking of the code to confirm that all programming logic which reflects the original model, in this case the "visual model" developed by the modeler to represent a certain "real" system, is correct. This aspect of programming has especially become easier with the latest Fortran compilers, which include built-in "debuggers". Also, static program analyzers have been developed, which can diagnose computer program code for inconsistencies, logic problems and other computer language errors. Despite all the new computer tools, however, the structure and logic of each new section or module still must be checked carefully. In addition, the models can be run through many different input combinations to verify that there are no actual errors or extreme results for a certain set of input conditions.

Calibration

Most modelers conduct experiments while they are developing models in order to have field measured data available for comparison with model predictions. Calibration of a model can generally be defined as quantifying the parameters and functions of a model so that predictions are the same or at least very close to the data obtained from field experiments. For the SOYGRO and PNUTGRO models in general, at least two independent data sets have been used for model development and calibration, while for the development and calibration of the BEANGRO model, two data sets from two completely different environments were used (Table 3).

In this article, only experimental data will be presented for soybean, although similar data sets have been used for both model calibration and validation of the PNUTGRO and BEANGRO models. More details about predictions by either PNUTGRO or BEANGRO can be found in Boote et al. (1985) and Hoogenboom et al. (1989). In figure 8, predictions of SOYGRO Version 5.42 are compared with field measured data for calibration. This experiment was conducted in Gainesville, Florida, during the summer of 1978; the soil was a Millhopper fine sand, the cultivar was 'Bragg', and the seeds were planted on 15 June. The top of figure 8 depicts the results from the irrigated experiment, while the bottom figure depicts the results from the rainfed experiment. Model predictions for total canopy, stem, leaf, and seed biomass compare reasonably well with these experimental data. Note that the soybean model responds

TABLE 3. Experimental data sets used for calibration of the BEANGRO, PNUTGRO, and SOYGRO crop simulation models

Year	Cultivar	Treatment	Location
		SOYGRO	
1978	'Bragg' Soybean	Irrigated and rainfed	Gainesville, FL
1981	'Cobb' Soybean	Irrigated and rainfed	Gainesville, FL
		PNUTGRO	
1976	'Florunner' Peanut	Irrigated	Gainesville, FL
1981	'Florunner' Peanut	Irrigated and rainfed	Gainesville, FL
		BEANGRO	
1986	'Porrillo Sintetico'	Irrigated	Colombia, S.A.
1986	'Porrillo Sintetico'	Irrigated and rainfed	Gainesville, FL

very well to drought and water stress; predicted seed yield for the irrigated treatment was 3000 kg/ha and for the rainfed treatment was 1000 kg/ha, very similar to the measured final yield data.

It was stated previously that the legume models also include cultivar specific parameters, allowing them to simulate growth and development for different cultivars. An example is shown in figure 9, in which measured and predicted biomass data of the cultivar 'Cobb' are shown. The experiment was conducted in 1981 at the same site as the 1978 experiment. Although the data in figure 9 only depict the irrigated treatment, other water management treatments were part of this experiment as well. 'Cobb' is a maturity group eight cultivar, while 'Bragg' is a maturity group seven cultivar. These specific growth and development parameters are defined in the genetics or cultivar specific coefficient file GENETICS.SB9. Similar genetics or cultivar specific parameter files exist for the other two models. The main differences between these two

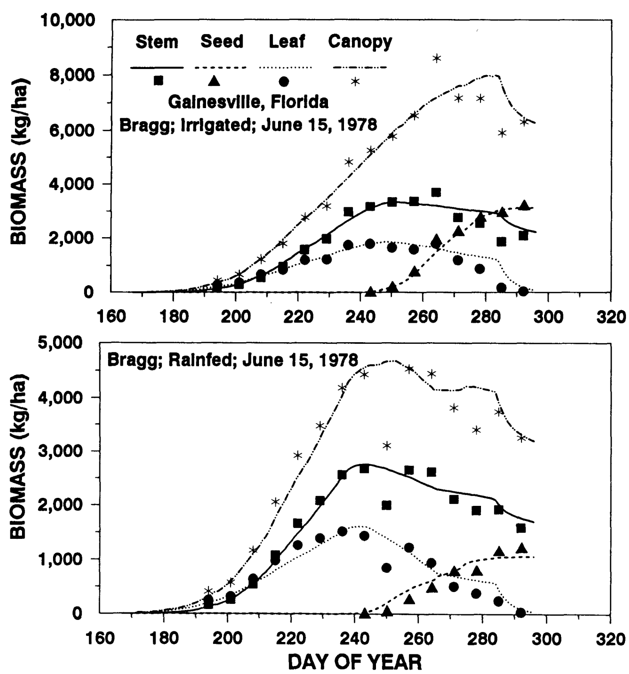

Figure 8–Measured (symbols) and predicted (lines) model development and calibration data for soybean cultivar 'Bragg' under irrigated (top) and rainfed (bottom) conditions.

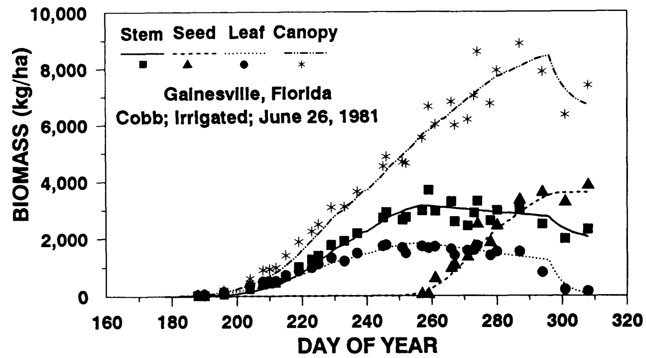

Figure 9–Measured (symbols) and predicted (lines) model development and calibration data for soybean cultivar 'Cobb' under irrigated conditions.

soybean cultivars are the parameters or coefficients which define the number of days between emergence and start of flowering, the number of days between start of flowering and physiological maturity, the sensitivity of each cultivar to photoperiod change, and the individual seed and shell growth rates. These are the major coefficients which are critical for correct predictions of growth and development for all three models.

VALIDATION

One of the important features of the IBSNAT crop simulation models is that they can be run for locations other than the site for which they were originally developed. There are many crop simulation models which can predict growth correctly for only one location. With the generic input files for the soil, weather, and crop management conditions, the user can easily create input files which correspond to his experimental conditions. As a result, the SOYGRO, PNUTGRO, and BEANGRO models have been run for many locations. Currently for SOYGRO there are more than 50 United States and 25 international data sets; for PNUTGRO there are more than 25 United States and 15 international data sets; and for BEANGRO there are more than 10 United States and 15 international data sets. These data sets have been used to validate the crop models for a wide range of soil, climatic, and management conditions. In addition, there are other data sets which have been created locally by scientists who received a copy of the model, but did not request any help from the model developers for calibration or validation of the models. The SOYGRO model, for instance, has been distributed to more than 275 users; the PNUTGRO model has been distributed to more than 150 users; and the BEANGRO model has been distributed to more than 75 users.

Validation, in general, is defined as the comparison of model predictions with experimental data which have not been previously used for model development and calibration, i.e., they are independent data sets. For most of the validation data sets, the only parameters which have to be defined are the genetic coefficients, similar to the model calibration procedures. Although the weather conditions, soil profile characteristics, and crop management are different for each experiment, they are considered to be fixed input values which cannot be changed. Sometimes an experiment is being conducted with a cultivar that has previously been defined. In this case, a "true" comparison can be made between model predictions and field measured data, using the original genetic coefficients defined from a previous experiment. However, if the experiment involves a cultivar which has not been defined in the genetics file of the model, the parameters which characterize this cultivar have to be defined. For these experiments, the genetic coefficients of the model have to be calibrated, and certain parameters have to be modified.

An example of model calibration for a new environment is shown in figure 10 for the cultivar 'Jupiter', a cultivar which is normally grown in the tropics (Caraballo de Silva, 1990). A general calibration of the genetic coefficients was done, although only three growth analysis samples were collected during the growing and yield and yield components were measured at final harvest. However, two experiments with different planting dates were conducted in Venezuela, giving a more robust estimation of the genetic coefficients. These coefficients were then used to simulate an experiment conducted in Costa Rica during the fall and winter of 1988. A comparison between field measured and simulated biomass for each of the three planting dates shows that model predictions were fairly accurate (fig. 11) (Arze Borda, 1989). The data presented in figures 10 and 11 are an example of a calibration of the model SOYGRO for one location, followed by a validation for another location, with a different set of environmental conditions.

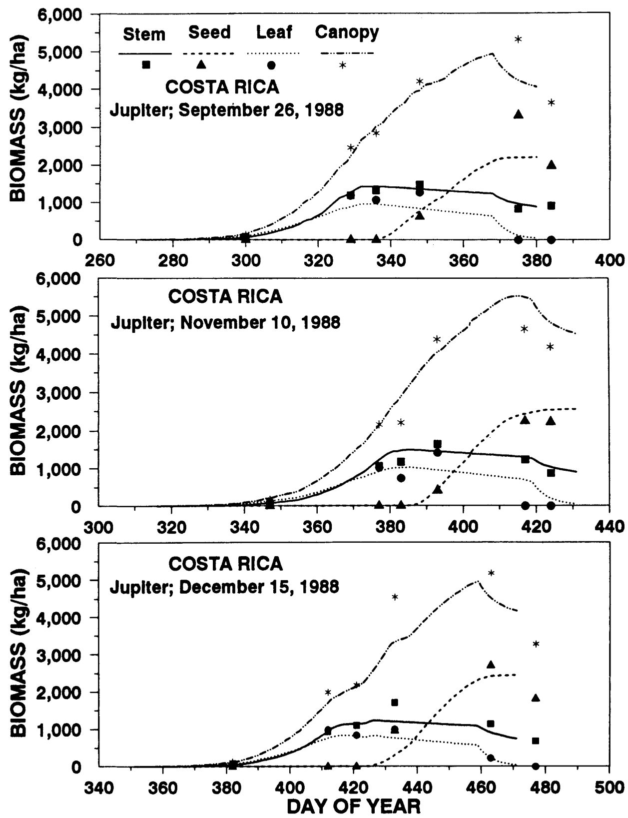

Figure 11–Measured (symbols) and predicted (lines) validation data for soybean cultivar 'Jupiter', grown in Costa Rica.

Model Applications

Many of the crop model applications have been in the area of crop management, especially with respect to application and control of irrigation (Fortson et al., 1989; Hood et al., 1987; Hoogenboom et al., 1991a; Jones and Smajstrla, 1980; Swaney et al., 1983). In some cases, the models have also been used to determine the effect of drought stress on crop production (Boote et al., 1985; Hoogenboom et al., 1988). The models have been integrated with economic analysis methods to estimate the risks which are involved with investments in irrigation or other crop management systems (Boggess and Amerling, 1983; Boggess et al., 1983; Wetzstein et al., 1988; Szmedra et al., 1988, 1990). Other applications have been in the area of disease and pest management (Batchelor et al., 1989a; Boote et al., 1983; Bourgeois, 1989; Jones et al., 1986; Mishoe et al., 1984).

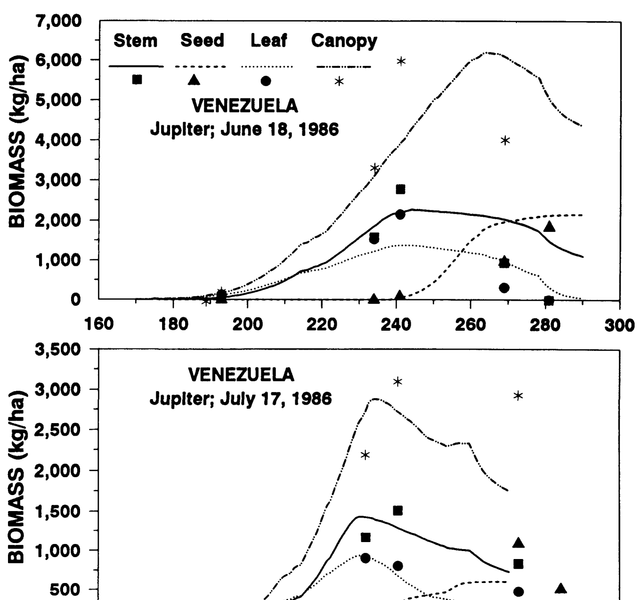

Figure 10–Measured (symbols) and predicted (lines) calibration data for soybean cultivar 'Jupiter', grown in Venezuela.

The potential impact of global climate change has recently received more attention (Smith and Tirpak, 1989), especially in the popular press. Any modifications of climate and instantaneous weather conditions, due to either the impact of a global climate change or other extreme weather conditions, will directly affect agricultural production (Curry et al., 1990a; Peart et al., 1988). SOYGRO was used to study the potential impact of global climate change on soybean production (Curry et al., 1990a,b). Similar applications also include the sensitivity of the models to change in temperature or photoperiod (Boote et al., 1989a; Hoogenboom et al., 1990a).

The crop models are being used in the research programs of the international research centers. BEANGRO was developed in collaboration with the bean program at the Centro Internacional de Agricultura Tropical in Colombia, South America. In a collaborative project with the International Center for Research in the Semi-Arid

Tropics, PNUTGRO is being used to study peanut yield potential in India for vegetable oil production. A case study is currently being conducted to use crop models and systems analysis techniques in the dry bean breeding program in Guatemala (Hoogenboom and Thornton, 1990).

In the United States, SOYGRO has been evaluated in a modeling project sponsored by the American Soybean Association. BEANGRO is used in an International Dry Bean Modeling Nursery in collaboration with dry bean breeders (Hoogenboom et al., 1990d, 1992). The models have also been incorporated as an extended knowledge base of expert systems or expert systems have been developed as a user-friendly interface for the models (Batchelor et al., 1989b; Lacey et al., 1989; McClendon et al., 1989). SOYGRO was coupled with the drainage model DRAINMOD (Perry et al., 1990). A new development is the integration of soil, weather, and other data bases into a Geographic Information System, linked with computer models, for land-use management and estimation of agricultural production on a spatial basis (Lal et al., 1990, 1992).

Since the development of the first version of the soybean model SOYGRO, many changes have occurred in both the grain legume models, agriculture, and the computer industry. The crop models have migrated from mainframe computers to personal computers and have become more user friendly. Agriculturalists have become more receptive to the use of computers and computer related technologies for research as well as for on-farm technologies. The models have been improved by the simulation of more plant processes and through calibration and validation with data sets from many different environments. During this evolution process of the models, it is important that they are continuously maintained and that changes and improvements are documented and distributed to the users. Part of the success of the models is reflected through their wide distribution. Although not everyone who requested a copy of the model is actually using it, researchers, extension personnel, consultants, and others are very interested in the systems analysis approach and are willing to apply these techniques in their own programs. These applications could be similar to the examples mentioned here and there could also be others.

The current models (Contact the senior author of this article to obtain information about the availability of the most current versions of the crop models SOYGRO, PNUTGRO, and BEANGRO.) were developed using an IBM AT and compatible microcomputers, PC-DOS version 3.30 and Microsoft Fortran version 5.0 (Microsoft Corporation, 10700 Northup Way, Bellevue, WA 98004).

Summary

This article presents a comprehensive review of the current status of the crop models SOYGRO, PNUTGRO, and BEANGRO. The first model developed was SOYGRO, and it only included a carbon balance simulation. Sections were added to simulate vegetative and reproductive development and a water balance. In addition, input and output sections of the models were standardized to fit within the IBSNAT crop model framework. The SOYGRO model was used to develop a model for peanut, i.e., PNUTGRO, and a model for dry bean, i.e., BEANGRO. The current versions of the models use soil, weather, and crop information as inputs. Species and cultivar specific information is handled by two special data files. The main processes simulated are vegetative and reproductive development, biomass growth and partitioning, and a soil and plant water balance. Simulations are initiated at planting, or earlier, to only simulate a soil water balance, and state variables are updated at daily time steps. Time series data are stored in output files and can be displayed at the end of the simulation. The development and calibration of these models was conducted with various experimental data sets collected in Florida and other locations. An example for model calibration and validation for a new cultivar, grown under tropical conditions, is presented. The models have been applied to study a wide range of topics related to both agriculture and the environment by researchers, extension agents, teachers, scientists, and others. Based on model user feedback, the models are being maintained and updated continuously.

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