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Crop Growth Modeling: A Review

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ABSTRACT

Crop/soil simulation models basically applied in three sections (1) tools for research, (2) tools for decision-making, and (3) tools for education, training and technology-transfer. The greatest use of crop/soil models so far has been by the research community, as models are primarily tools for organizing knowledge gained in experimentation. However, there is an urgent need to make the use of models in research more relevant to problems in the real world, and find effective means of dissemination of results from work using models to potential beneficiaries. Nevertheless, crop models can be used for a wide range of applications. As research tools, model development and application can contribute to identify gaps in our knowledge, thus enabling more efficient and targeted research planning. Models that are based on sound physiological data are capable of supporting extrapolation to alternative cropping cycles and locations, thus permitting the quantification of temporal and spatial variability. Over a relatively short time span and at comparatively low costs, the modeler can investigate a large number of management strategies that would not be possible using traditional methodologies. Despite some limitations, the modelling approach remains the best means of assessing the effects of future global climate change, thus helping in the formulation of national policies for mitigation purposes. Other policy issues, like yield forecasting, industry planning, operations management, consequences of management decisions on environmental issues, are also well supported by modelling. Models are not simple mechanisms to archive and synthesize information for producing forecasts. Modelling represents a better way of synthesizing knowledge about different components of a system, summarizing data, and transferring research results to users.

INTRODUCTION

Crop is defined as an “Aggregation of individual plant species grown in a unit area for economic purpose”. Growth is defined as an “Irreversible increase in size and volume and is the consequence of differentiation and distribution occurring in the plant”. Simulation is defined as “Reproducing the essence of a system without reproducing the system itself”. In simulation the essential characteristics of the system are reproduced in a model, which is then studied in an abbreviated time scale.

A model is a schematic representation of the conception of a system or an act of mimicry or a set of equations, which represents the behaviour of a system. Also, a model is “A representation of an object, system or idea in some form other than that of the entity itself”. Its purpose is usually to aid in explaining, understanding or improving performance of a system. A model is, by definition, “A simplified version of a part of reality, not a one to one copy”. This simplification makes models useful because it offers a comprehensive description of a problem situation. However, the simplification is, at the same time, the greatest drawback of the process. It is a difficult task to produce a comprehensible, operational representation of a part of reality, which grasps the essential elements and mechanisms of that real world system and even more demanding, when the complex systems encountered in environmental management.

The Earth's land resources are finite, whereas the number of people that the land must support continues to grow rapidly. This creates a major problem for agriculture. The production (productivity) must be increased to meet rapidly growing demands while natural resources must be protected. New agricultural research is needed to supply information to farmers, policy makers and other decision makers on how to accomplish sustainable agriculture over the wide variations in climate around the world. In this direction explanation and prediction of growth of managed and natural ecosystems in response to climate and soil-related factors are increasingly important as objectives of science. Quantitative prediction of complex systems, however, depends on integrating information through levels of organization, and the principal approach for that is through the construction of statistical and simulation models. Simulation of system's use and balance of carbon, beginning with the input of carbon from canopy assimilation forms the essential core of most simulations that deal with the growth of vegetation.

CROP GROWTH MODELS

Agricultural models are mathematical equations that represent the reactions that occur within the plant and the interactions between the plant and its environment [1]. The model simulate or imitates the behaviour of real crop by predicting the growth of its components, such as leaves, roots, stems and grains. Thus, a crop growth model not only predicts the final state of total biomass or harvestable yield, but also contains quantitative information about major processes involved in the growth and development of a plant.

Types of Models

Basically, crop growth models can be distinguished as,

Empirical/Corrective Models

It simulates the behavior of a system in a simple way. It describes the relationship between variables without referring to any underlying biological or physical structure that may exist between the variables. A system is defined as any well delimited part of the real world and for an agronomist, this may be a crop with its elements, plant organs (such as leaf, stem and root) and process (such as growth, transpiration etc.). In this type of models experimental data are used to find one or more mathematical equations which are able to describe the behaviour of the system.

An example of this approach as shown in Fig.1, where the regression equation is derived from successively measured weights of a maize crop [2]. However, since the behaviour of the crop will not be the same when soil, Crop practices and weather are different, large deviations can result from differences in weather pattern between years (Fig.2). In theory it is possible to derive the required constants and equations with good accuracy from many experiments; but then in practice, many variables influence growth pattern of a crop, and thus it is impossible to quantify in a correct way all variables through extensive field experiments. Corrective models are therefore of interest only when a quick tool is required to describe the behaviour of a crop under field condition and where conditions remains relatively stable.

Mathematical/ Explanatory Models

On the other hand explanatory models consist of a quantitative description of the mechanisms and process that guide the behaviour of the system. In order to create explanatory models, the system is analysed and its processes and mechanisms are separately quantified. The model is then built by integrating these for whole system. An explanatory crop growth model calculates rate variables (photosynthesis rate, leaf area expansion rate *etc.*) and state variables (crop biomass, yield *etc.*). Processes are quantified as a function of environmental factors, such as radiation, temperature, etc., and in relation with the state of the crop, including leaf area, development stage and nutrient availability. In this way growth rates can be computed at each plant stage during the growing season, on the basis of the status of the crop, soil and weather. In general the number of the processes of the prime importance for simulating crop growth is limited and detailed calculations such as the efficiency of synthesis of each biochemical compound in a biomass or the dynamic aspects of cell physiology are not necessary. However, the numbers of processes that have to be included in a crop growth model depend on

- The detail required in the results of the model,
- The growth-limiting factors considered in the model (such as water or nutrients shortage)

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The relational diagram in Fig. 3 indicates the processes and the environmental factors that are considered in a growth model of crop without water and nutrient shortage. Light and temperature are the driving variables of the system and assimilation, development, respiration, conversion and portioning of assimilates between organs are the principle processes considered in the model.

Level of Details Considered in the Model Building

Every modeler must consider the level of detail at which a given model should be developed. The level of detail is also linked to the objectives of the model, as discussed earlier. The Fig.4 shows the hierarchy of the various levels at which models can be built. With these levels are shown the usual time frames (that is time steps used in running the models) and the usual data bases for building the models. Generally, models low in the hierarchy use a small time frame and require data from detailed experiments performed in closely defined conditions. Models low in the hierarchy also tends to be models of individual processes. These can be aggregated to form models at higher levels in the hierarchy, but there are limits on the extent to which this is feasible.

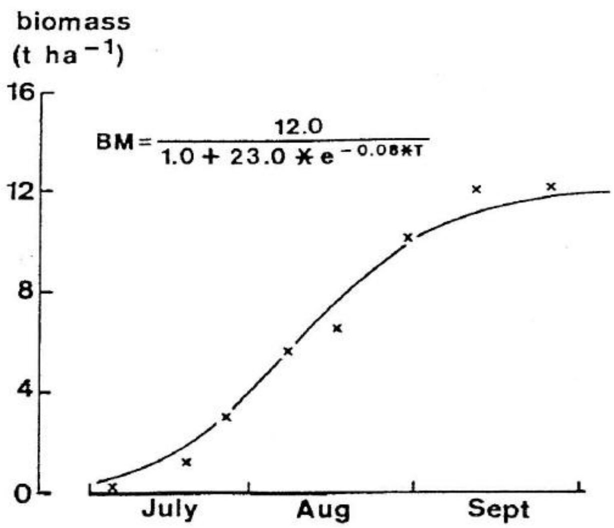

Fig. 1 - The coarse of the the dry weight of a maize crop in the Netherlands in 1972. Crosses represent observations, the line the regression equation. BM = biomass in t ha^{-1}, T = time in days since emergence (Source: Penning de Vries et al., 1989).

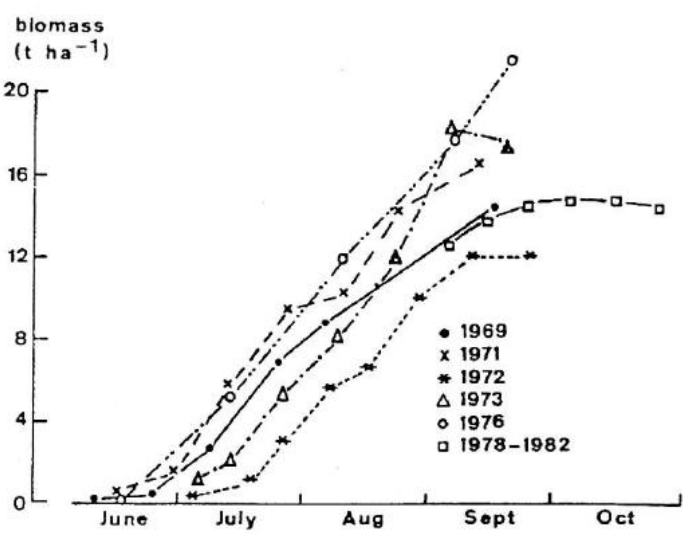

Fig. 2 - The dry weight of maize crops under optimal conditions in different years in the Netherlands (Source: Sibma, 1987).

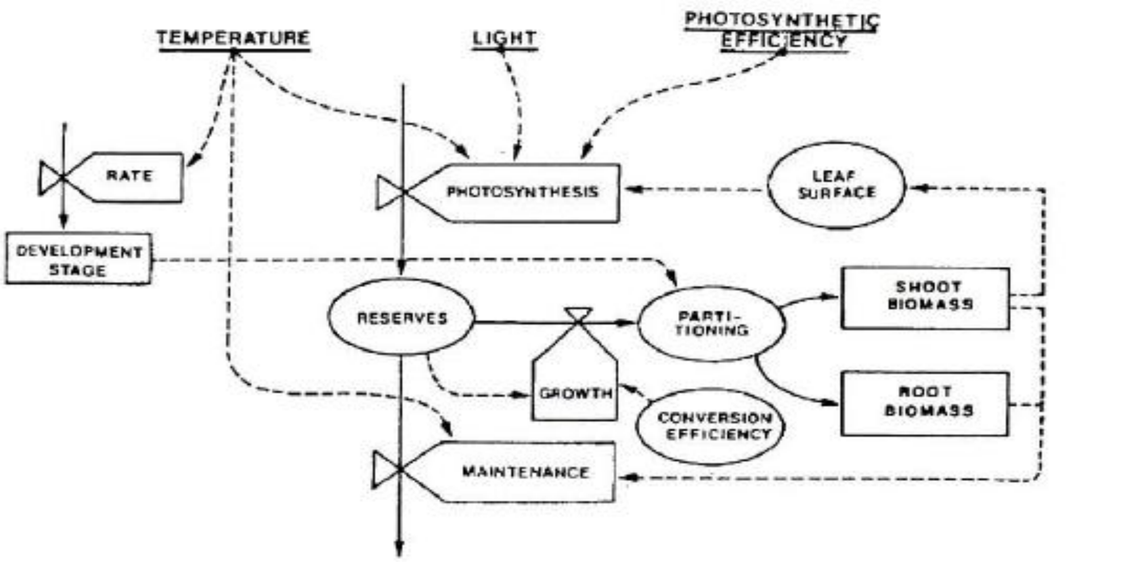

Fig. 3 - A relation diagram of a growth simulation model for a crop without water and nutrients shortage. (Source: Penning de Vries et al., 1989).

Crop Simulation Models

- Computer models, mathematical representation of a real world system.
- Main goals – to estimate agricultural production as a function of weather, soil conditions and crop management.
- Use one or more sets of differential equations, and calculate both rate and state variables over time, normally from planting until harvest maturity or final harvest.

In addition to the types of models already described, some further definitions are needed like,

Dynamic Crop Simulation Models: These models predict the changes in crop status with time as a function of exogenous parameters. For example, models that predict the changing number of bolls on a cotton plant throughout the growing season, or the changing soil water content or temperature at a certain depth throughout the season, are dynamic simulation models.

Phenological Models: Are the broad classes of models that predict the crop development from one growth stage to another. These predictions are generally based upon the accumulated heat units, with development being delayed by various stresses. These models may or may not be based upon mechanistic concepts.

Stochastic Models: Are those that are based upon the probability of occurrence of some events or exogenous variables. They may have mechanistic sub models or subroutines. Weather variables are often treated in a stochastic manner or probability of occurrence and as such may be combined with a mechanistic crop model. The same might also be done with insects, diseases and weeds.

Physically and Physiologically Based Simulation Models: Are those mechanistic models whose plant or soil processes can be physiologically, physically or chemically described. For example, nitrogen may be taken up from the soil by root systems based upon the soil nitrogen content and the rate of solution flow to the root. Thus the physical placement of the fertilizer with regard to the plant root system is important as well as soil and plant nitrogen transformation.

Surrogate Variables

Those variables that are calculated by the model and used to estimate value of another quantity that the model does not directly calculate.

Ex. Some modelers calculate dry matter production rate from the estimated transpiration rate, citing Tanner (1974) observation of an impressive linearity between transpiration and yield [3].

Table 1: List of some published crop models

Sl. No.	Model name	Species	Processes treated
1	GLYCIM	Soybean	Photosynthesis, respiration, transpiration and morphogenesis
2	IRRIMOD	Rice	Growth, phasic development, soil water flow, soil nitrogen , transpiration and evaporation
3	SORG	Sorghum	Photosynthesis, respiration, transpiration and evaporation
4	GOSSYM	Cotton	Photosynthesis, respiration, transpiration, growth and morphogenesis
5	COTCROP	Cotton	Photosynthesis, respiration, transpiration, runoff, drainage, N uptake, denitrification, leaching, partitioning and growth
6	SOYMOD	Soybean	Photosynthesis, respiration, transpiration and evaporation
7	SIMAIZ	Maize	Photosynthesis, processes involved in setting seed number and seed size
8	PEANUTZ	Peanut	Photosynthesis, N fixation, processes involved in setting seed number and seed size
10	RHIZOS	Soil	Infiltration, uptake, capillary redistribution, ET, N transformation, N fertilizer application
11	POTATO	Potato	Photosynthesis, respiration, transpiration, water uptake, growth, development and senescence
12	CERES-Wheat	Wheat Maize Rice Barley Sorghum Millet Dry bean Peanut Soybean Potato Cassava	Phenologic development, canopy development, organ formation, photosynthesis, assimilates allocation, and carbon, water and nitrogen dynamics in the soil and plant.
13	SOYGROW	Soybean	Photosynthesis, respiration, growth, senescence, phenology, infiltration, drainage and transpiration
14	INFOCROP	Maize Wheat Cotton Barley Rice	Crop growth and development, effects of water, nitrogen, temperature, flooding and frost stresses on crop growth and development, crop-pest interactions, Soil water balance, soil nitrogen balance, soil organic carbon dynamics and emissions of green house gases
15	AQUACROP	Water uptake	Water uptake, effect of water stress on crop growth and development, infiltration, transpiration and evaporation.
16	GMDSSCM	Wheat Rice Cotton rape	Phasic and Phenological development, morphological and organ formation, photosynthesis and dry matter accumulation, yield and quality formation, soil water relation and dry matter accumulation and dynamic nutrient (N, P and K) balance in soil and plant system.
17	WTGROWS	Wheat	Photosynthesis, respiration, growth, senescence, phenology, infiltration, drainage and transpiration
18	FIELD	Crop-soil system	Simulate the crop productivity and long term changes in soil C and nutrient stocks at field.
19	C- Farm	Soil	Carbon balance of soil profiles
20	HYBRID-maize	Maize	Temperature driven maize development, vertical canopy integration of photosynthesis, organ-specific growth respiration and temperature sensitive maintenance respiration.
21	DUET	Soil surface mgt.	To evaluate varies types and frequencies of conservation tillage, infiltration and evaporation, and growth and development of crops
22	PERFECT	Soil surface mgt.	To evaluate various management practices like, crop/fallow sequences, tillage

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			and addition of soil ameliorates to modify infiltration, evaporation and erosion
23	PARCHED-THIRST	Water	Rain water harvesting
24	EPIC	Soil water	Effect of water depletion on crop growth
25	CROPSYST	Soil water	Effect of water depletion on crop growth
26	CANESIM	Sugarcane	Irrigation scheduling in sugarcane
27	CROPWAT	water	Designing new irrigation schemes and introducing new crops that requires irrigation
28	INTERCOM	weed	Simulated competition for light and water between crop and weeds
29	SOYWEED	weed	Simulated competition for light and water between soybean and weeds

Table 2: Simulation models for prediction of insects and diseases

Model name	Crop	Diseases
BLIGHTCAST	Potato	Late blight in England
EPIDEM	Potato and tomato	Early blight
JHULSCAST	Potato	Late blight in India
EPIDEMI	Wheat	Insects-pests and scab
EPIBLAST	Paddy	Blast
CERCOS	Celery	*Cercospora* leaf spot
EPICORN	Maize	Southern leaf blight
EPIVEN	Apple	Scab
PLASMO	Grapes	Downy mildew
MYCOS	Chrysanthemum	*Mycospherella* leaf spot
TOMECAST	Tomato	Early blight
EPICAST	Wheat	Leaf rust
MARYBLIGHT	Apple	Fire blight
EPIPREY	Wheat	6 foliar diseases and aphids

Principles of Crop Growth Modeling

According to Day and Atkin (1984) good model building requires [4],

- A sound appreciation and understanding of the biological problem, though not necessarily including the most intricate details
- A realistic mathematical representation of the phenomenon
- Finding a solution, quantitative if possible, of the resulting mathematical problems
- A biological interpretation of the results, ideally giving biological insight and predictions

Important Plant Process to Be Understood While Developing a Model

Crop Physiology and Morphology

Primary process involved:

Light interception

Light or more exactly, photosynthetically active radiation supplies plants with energy for CO_2 fixation. It is fairly obvious that the amount of light intercepted depends on the leaf area of the crop, and this is usually expressed as leaf area index. However, it is quite obvious that leaves on a crop and even a single plant shade each other and light interception cannot be directly proportional to leaf area index.

CO_2 Fixation

It has often been observed that crop dry weight gain is approximately proportional to the total canopy light interception. This relationship used in some models to simulate predict dry weight gain but suffers from the problem that the parameter values needed to be varied form one year to the next Because of this problem, most crop models deal mechanistically with the processes involved in CO2 fixation.

Partitioning

Some modelers use empirical partitioning factors which they vary from stage to stage in the plant's development [5]. Other modelers partition carbon according to the potential of the various organs on the plant for growth [6].

Tissue expansion

Very few crop models deal with the tissue expansion explicitly. In many of the models that do, only leaf tissue expansion is important. Usually, the increment of dry matter partitioned to leaves is multiplied by specific leaf area to give the increment of increase in leaf area.

Morphology

Crop morphology is the resultant of two independent processes: organ initiation and organ abortion. Clearly these are distinctly different processes responding to different plant and environmental factors, and hence, they must be modeled separately [7]. For most plants, the rate of appearance of new nodes on any axis is a function of water, nitrogen, etc., but in other species the rate is influenced very little by these factors unless they are in very short supply, the expansion of leaves, petioles, and stem internodes will all be inhibited but new leaves will continue to appear at a rate dependent only on temperature.

Phenology

Because of early successes with heat units in predicting the timing of growth stages in maize, modelers have tended to assume that the heat unit concept is universally applicable. The theoretical basis for the technique is that, of the processes in crop development, all are sensitive to temperature and one will be limiting. The temperature response of the limiting processes will be the temperature response of overall crop.

Limits and Stresses

Crop modelers find all too frequently that the equations they have written to describe some process, under certain combinations of circumstances, allow the rate of process to increase without limit. Similarly, the equation may predict rates for the process that are too low or even negative.

Soil process

Water movement

Many models used daily total rainfall, but recently planning to change this to hourly or more frequent measurement for on farm versions of the model. Rain water enters the surface soil fills the profiles, layer by layer, until that horizon's "field capacity water content" is reached. Excess rainfall is counted as deep seepage or runoff.

Evapotranspiration

A simple equation used to estimate the evaporation by most of the modelers is the Penman equation (Penman, 1963). It requires the knowledge of solar radiation, wind speed, temperature, air humidity, and the albedo of the soil and crop.

Soil Temperature

Heat fluxes at the soil surface: at the soil surface, heat is gained from solar radiation and lost by evaporation, reradiation and convection to the atmosphere and by conduction to lower layers of the soil. Heat fluxes within the soil: an excellent, and perhaps the only, source of ideas about the mechanisms governing heat transfer in soils is De Varies, 1966. He has developed equations to calculate soil thermal diffusivity from soil texture, organic matter content, water content, and total pore space.

Soil Mechanical Impedance

The effects of soil mechanical impedance are calculated in the root impedance and root growth subroutines. The relationship between soil penetration resistance and root growth was,

$$RG = 104.6 - 3.53PR$$

Where,

RG= percentage root growth compared to nonimpeded growth

PR= penetration resistance in dynes per square centimeter

Soil Oxygen Content

The oxygen concentration is calculated for the soil profile using apparent diffusion coefficients and root-soil oxygen consumption rates as functions of the calculated soil water content, temperature and root densities.

Nitrogen Transformation

It accounts for the changes from organic to ammonium to nitrate forms of nitrogen. The nitrate ions are assumed to be immobile.

Pests

Simulations of insects, weed and nematode populations and epidemiology of plant pathogens are premised on a detailed understanding of biological, ecological and behavioral responses and damage capability of each species in relation to biotic and abiotic and abiotic factors in the environment.

Data Acquisition

Data Needed To Run Crop Simulation Models

Depend on- Species under consideration and the type of model to be constructed. Essentially all simulation models require information about the initiation, growth and abortion of organs on the plant as affected by the relevant environmental and physiological variables.

a. Field experiments: Conduct the experiment with optimum growing condition. Then, measure and quantify the light interception, respiration, transpiration and Photosynthesis of the whole plant system. Repeat the experiment under resource limited condition and measure and quantify the plant process which is affected.
b. Controlled environment experiments:

Sunlight or air tight chambers- SPAR (Soil-Plant-Atmosphere Research)

Phytotran studies

Open top chambers

In all controlled experiments, sampling for dry weight is a problem because it results in loss of canopy, extra rows of plants can be grown during the seedling stage without affecting the permanent plants and dry weight can be measured at final harvest.

Data needed to Run Crop Simulation model

All crop simulation models requires as input, data on the management of the crop, as well as the macro and micro environmental factors associated with the weather and the soil. Management data consist of the latitude of the site, row spacing, plant population, amount and timing of fertilizer applications, and similar information. However, when modelers ask experimentalists to collect detailed data about the weather and soil, the significance of the request is not always understood.

a. Meteorological Data

- Tmax and Tmin
- Total solar radiation
- Precipitation
- Humidity (0900 hrs)
- Wind speed

b. Soil Data

- Depths of the major soil horizons
- For each horizon, the particle size analysis, BD, water release curve and saturated HC
- Residual fertilizer content at the start of the season
- Organic matter content at planting
- Soil temperature

c. Crop Management Data.

d. Crop Coefficients.

Model Calibration/ Verification

After constructing the model one must ask three questions,

- To what extent does the mathematical model represent reality?
- Is the model exactly represented by the computer program?
- Are the experimental data correct?

In many instances, simulated values do not exactly comply with the observed data and minor adjustments have to be made for some parameters. To make the model work correctly, some of the parameters in the equations and even some of the relationships have to be adjusted. This process is called as calibration.

Tools for Model Calibration

- Using the SI system throughout the program and checking of the units of all equations,
- developing the mass balances for the state variables,
- comparison of numerical and analytical solutions, usually for portions of the model,
- performing a robustness test using extreme, but realistic, parameter values to investigate whether the program fails or shows strange behavior, and
- Performing a sensitivity analysis (how strongly does model output change compared to a change in the input), both with respect to parameters and structure of the model.

Sometimes it is necessary to recalibrate a model when a different soil type, cultivar, *etc.,* is to be simulated. For example, in soybeans, much of the variation between cultivars can be explained by maturity group number. The existence of parameters that have to be altered alerts us to the fact that our model is not as universally applicable as we might have supposed. Either there is a problem with some mechanism or we need additional input data. Even when simulation models have to be recalibrated for different situations, they can still be useful so long as the recalibration procedure is simple.

Model Validation

Testing model performance during development of a model usually results in calibration, which is, according to Penning de Vries (de Vries and von Laar, 1982) a "very restricted form of evaluation," and "adjustment of some parameters such that model behavior matches one set of real world data." It can "degrade simulation into curve fitting."

Before any model can be used with confidence, adequate validation or assessment of the magnitude of the errors that may result from their use should be performed. Model validation, in its simplest form, is a comparison between simulated and observed values.

Beyond comparisons, there are several statistical measures available to evaluate the association between predicted and observed values, among them the correlation coefficient (r) and its square, the coefficient of determination (r^2).

Test criteria have been separated into two groups, called summary measures and difference measures. Summary measures include the mean of observed values (0) and predicted values (P), the standard deviations of observations (S_o) and the predictions (S_p), the slope (a) and intercept (b) of the least-squares regression:

$$Pi = a + b * 0i$$

In addition, an index of agreement (d) (Willmott, 1982) was calculated as follows:

$$d = 1 - [S (P - O) / S (|P'| + |O'|)], 0 \leq d \leq 1$$

where P' = P - O and O' = O - O

Though (d) is meant to be used mainly to determine the relative superiority of alternative models, it can be valued as a descriptive parameter of model performance. The more (d) approaches 1, the more accurate the model.

While summary measures describe the quality of simulation, difference measures try to locate and quantify errors. The latter includes the mean absolute error (MAE), the mean bias error (MBE), and the root mean square error (RMSE). They all are calculated according to Willmott (1982) and based on the term ($P_i - 0_i$):

A) Mean Absolute Error (MAE): $MAE = S \mid P_i - 0_i \mid / n$
B) Mean Bias Error (MBE): $MBE = S (P_i - 0_i) / n$
C) Root Mean Square Error (RMSE): $RMSE = S (P_i - 0_i)^2 / n$

MAE and RMSE indicate the magnitude of the average error, but provide no information on the relative size of the average difference between (P) and (0). MBE describes the direction of the error bias. Its value, however, is related to magnitude of values under investigation. A negative MBE occurs when predictions are smaller in value than observations.

In the test of data sets without N routines, attention was focused on the unsystematic error ($RMSE_u$) as in the system: $MSE = MSE_s + MSE_u$

For a good model, the unsystematic error RME should approach RMSE, with $RMSE_s$ approaching 0/, which is what could be observed.

The parameters examined in the statistical evaluation were:

1. Anthesis date
2. Maturity date
3. Leaf area index (LAI) at maximum
4. Total above ground dry matter at maturity
5. Grain yield
6. Individual grain weight at maturity
7. Number of grains per m_2 at maturity
8. Dry matter at anthesis
9. N uptake by the crop at anthesis
10. N uptake in the above ground plant parts at maturity

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11. N content of the grain
12. Grain protein percentages

CONCLUSION

Crop/soil simulation models basically applied in three sections (1) tools for research, (2) tools for decision-making, and (3) tools for education, training and technology-transfer. The greatest use of crop/soil models so far has been by the research community, as models are primarily tools for organizing knowledge gained in experimentation. However, there is an urgent need to make the use of models in research more relevant to problems in the real world, and find effective means of dissemination of results from work using models to potential beneficiaries. Nevertheless, crop models can be used for a wide range of applications. As research tools, model development and application can contribute to identify gaps in our knowledge, thus enabling more efficient and targeted research planning. Models that are based on sound physiological data are capable of supporting extrapolation to alternative cropping cycles and locations, thus permitting the quantification of temporal and spatial variability. Over a relatively short time span and at comparatively low costs, the modeler can investigate a large number of management strategies that would not be possible using traditional methodologies. Despite some limitations, the modelling approach remains the best means of assessing the effects of future global climate change, thus helping in the formulation of national policies for mitigation purposes. Other policy issues, like yield forecasting, industry planning, operations management, consequences of management decisions on environmental issues, are also well supported by modelling.Models are not simple mechanisms to archive and synthesize information for producing forecasts. Modelling represents a better way of synthesizing knowledge about different components of a system, summarizing data, and transferring research results to users.

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