1.3 Phases of development of models

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1.3.1 Phases of development

For more than a decade models have been used to simulate plant growth and crop productivity. The processes of the carbon balance and water balance have been strongly emphasized. As a result many aspects of models at the Production levels 1 and 2 are now well developed, as is demonstrated in the Sections 3.1-3.4 and 4.1-4.3. For a few years now, some simulation studies direct themselves towards relationships of plant growth and availability of nutrients from the soil. However, knowledge of the underlying processes is as yet little developed. As a consequence, their models are still less advanced (Sections 5.1-5.3; Penning de Vries, 1980).

Models of plant growth and production can be divided into classes: preliminary models, comprehensive models and summary models. Such phases of evolution of models are discussed here briefly, and more extensively in other literature (Penning de Vries, 1982b).

During development, a model moves gradually from one phase into the next. Preliminary models are defined as models with structure and data that reflect current scientific knowledge. They are considered simple because insight at the explanatory level is still vague and imprecise. A comprehensive model is a model of a system whose essential elements are thoroughly understood, and in which much of this knowledge is incorporated. Summary models are models of comprehensive models: in them essential aspects of the comprehensive models are formulated in less detail than is possible. This is done to simplify the model and to make it more accessible for users. Summary and comprehensive models are found at the levels of production where soil moisture or weather limits growth, whereas models for the production levels where nitrogen or phosphorus is the main limiting factor are predominantly of the preliminary type, or even basically a regression of yield to an environmental variable. The models of these three developmental stages differ considerably in their value for instruction, for prediction, for scientific progress and in simplicity (see Subsection 1.3.5). Table 1 rates them on an arbitrary scale.

The division of dynamic models into three classes is obviously an oversimplification. Particularly those models that have been developed over a long period and that are still being improved consist of submodels of which some are in fact summary models, others are comprehensive in nature, and still others are preliminary submodels. The characteristics given for the three phases of development of models apply then to the individual submodels. The coordination of submodels within the framework of a large model is discussed in Section 1.4.

1.3.2 Preliminary models

At the frontiers of knowledge, preliminary models are very common. They enable the quantification and evaluation of hypotheses and are useful as such, but they seldom survive a long time. The category of preliminary models shows the largest diversity of hypotheses on processes and their relationships on the explanatory level, making these models highly interesting for scientists and stimulative for experimental research. See for example Subsection 5.2.1. Their predictive value is generally fairly low. If preliminary crop growth models are presented unreservedly, one often finds that potential users are actually discouraged as a result.

A typical preliminary model is that of tulip growth by Rees & Thornley (1973). It is a very small model of growth of individual plants that describes in an unrefined way all essential processes. It consists of only 18 simple computer statements and describes the carbon flow from a mother bulb to the developing top and to the daughter bulb from top emergence until leaf death. The top is supposed to grow heterotropically, while the daughter bulb utilizes mother bulb reserves and monopolizes also all photosynthetic products. Net plant CO_2 assimilation equals top weight times the incident irradiation intensity times a constant. Emergence and death occur at fixed dates. This model is labelled preliminary because of the very simple description of the CO_2 assimilation, respiration and growth processes, and because of the absence of any consideration of environmental conditions on the date of emergence and the rate of plant development. Unfortunately, only very few preliminary models have the elegant simplicity of this tulip-growth model.

Most of the models on growth under nutrient stress fall in this group, as essential processes in plants and soils are still little understood, the physiological effects of extreme shortage of some microelements being an exception (cf. Wright, 1977). Models to simulate the morphological development of plants and of its organs are also still of a preliminary nature, or even purely descriptive. Section 3.4 discusses some of their features.

1.3.3 Comprehensive models

Comprehensive models are developed from preliminary models as a result of scientific progress: more knowledge and insight become available, so that the functioning of the real system becomes more lucid, and its simulation becomes more truthful. The expectation that such models may become finally predictive tools can provide a strong motivation for their construction. Comprehensive models are explanatory models par excellence: their behaviour can be explained fully from the well known underlying processes that are integrated in them. However, models of this group are often large, intricate and unwieldy, so that in practice they can only be used by those who participated in their development. Because large and complex models are almost impossible to communicate in full to potential users, this phase of comprehensive models should not be considered as a final stage, but summarization should necessarily follow it. But though the summary model of a system may become the most utilized model of a system, in some cases it remains necessary to employ the full, complex model. This will be required when a high accuracy of results is needed, but also to check whether modifications of existing summary models are implemented correctly.

The model BACROS is an example of a comprehensive model. It simulates vegetative growth of crops at non-limiting levels of soil water and soil nutrients on basis of standard meteorological observations and many physical, biochemical and physiological characteristics. In its current stage, neither germination nor the reproductive growth phase is considered. The model has been developed over more than a decade by de Wit and a team of co-workers (de Wit et al., 1978); it is described to a large extent in the Sections 3.2 and 3.3. Laboratory research, literature study and frequent evaluations led to a model that simulates growth, yield and water use quite reliably over a wide range of environmental conditions for annual crops of C_3 and C_4 type species. Its structure reflects cereal and grass crops, and small but specific sets of parameters and functional relationships specify the actual species under consideration. The model is adaptable to other types of species. Like all models in this group, BACROS is still particularly weak in the simulation of regulation of distribution of biomass, and in development of leaf surface area. The latter limitation is a handicap for the early stages of growth, and to its transferability to other geographic areas.

It is not by accident that the current comprehensive models are all at the Production levels 1 and 2. Processes of the carbon balance and water balance received much attention from crop physiologists and from soil physicists. However, as most farming is done under nutrient stress, the practical utility of the current comprehensive models is still largely restricted to setting maxima for yield potentials and establishment of the contribution of the individual processes and factors to it (de Wit & Penning de Vries, 1982).

1.3.4 Summary models

Summarizing a comprehensive model can and should be done to make it more accessible to others in an intellectual and a practical sense. The extent to which summarization is useful depends on many factors, among which future use of the model and its inherent complexity, but simplification should achieve a level at which the model becomes really accessible to non-specialists. In the process of summarization, it is essential to indicate specifically the limits within which the model is valid. Construction of summary models should be done by scientists who know the comprehensive model by heart, and who are in contact with potential users for suggestions in which direction and to what extent to summarize it. Unfortunately, modellers may not always be motivated to do so, as the process provides little scientific challenge. Summary models can be made by shedding all excessive detail, using sensitivity analysis and by regression of model results to the main driving variable of the system. An example of the result of the first procedure to obtain a summery model is presented in Section 3.1, a result of the second procedure in Section 3.2. The latter case concerns a summary of a canopy CO_2 assimilation model. Without loosing much flexibility, a large model could be reduced enormously because there are few interactions of the CO_2-assimilation processes with the environment. See also Section 1.4 on coordination of models.

It will be obvious that THE summary model of any comprehensive model does not exist: different summaries can be made with different degrees of depths and for different purposes. The summary model in Section 3.1 of growth of a crop is a small simulation model, and it is meant for use on a computer system upon which the simulation language CSMP (see Section 2.2) is available. By specifying a few crop-specific parameters, different types of annual crops can be simulated. Considerably simpler than this summary model is an earlier model by van Keulen (1976) about the potential production of rice crops. Its size, and the amount of calculations required for the simulation are such that the complete model can be programmed on a pocket calculator. Its basis is an equation in which the growth rate (GTW, in kg ha^{-1} d^{-1}) can be given as:

$$GTW = (DTGA \cdot 0.68 - MC \cdot TWT) \cdot CVF$$

DTGA stands for gross CO_2 assimilation (in kg ha^{-1} d^{-1}; a factor of 0.68 converts it to glucose assimilation, in kg ha^{-1} d^{-1}), TWT for total dry weight (kg ha^{-1}), MC for the maintenance coefficient in glucose per dry matter (kg kg^{-1} d^{-1}) and CVF for the conversion efficiency of glucose for the growth process (kg kg^{-1}). Van Keulen distributes biomass formed in one time step over roots, leaves, stems and, after flowering, over inflorescences plus seeds in predetermined proportions related to the physiological age of the crop. DTGA is calculated from standardized data. The leaf surface area, required in the CO_2 assimilation calculation, is found by dividing the leaf weight by 1000 kg ha^{-1}. MC reflects the energy requirement to maintain living tissues in their current state, and has a value of 0.02-0.015; the effect of temperature on MC could be neglected as this model was applied in a fairly constant environment. CVF is only a function of the chemical composition of the biomass formed; a value of about 0.7 is common (Subsection 3.3.4). Final yield is calculated by proceeding with time steps of 10 days and adding the biomass increment to the biomass already present.

The interested reader is invited to compare both summary models for his own purpose on aspects such as simplicity in use, accuracy in results, flexibility for adaptations to specific conditions of crop parameters.

1.3.5 Uses of models

A model is a tool that can be useful for development of science, for prediction and for instruction, but not for each aspect to the same extent: scientifically in-

Table 1. The relative values of certain aspects of models in different stages of development (the more plusses, the higher the value).

	Predictive value	Scientific value	Instructive value	Simplicity
Preliminary model	+	+ + +	+ +	+ +
Comprehensive model	+ +	+ + +	+	+
Summary model	+ + +	+	+ + +	+ +

teresting models are often too detailed for those who want to apply them, while models used for predictive or management purposes are often too trivial or crude to challenge scientific interest. Table 1 characterizes models in different stages of development in this respect.

A scientifically interesting model contributes to our understanding of the real world because it helps to integrate the relevant processes of the system and to bridge areas and levels of knowledge. It helps also to test hypotheses, to generate alternative ones and to suggest experiments to falsify them. Subsection 3.3.8 provides an interesting illustration. A predictive model should simulate accurately the behaviour of a part of the real world. It is therefore a good instrument to apply scientific knowledge in practice. It should predict reasonably well over a range of boundary conditions to provide its users with alternative solutions of a problem. The less detailed the desired results are, the simpler the predictive model can be. The instructive value of a model is its use for propagation of knowledge.

The size of a model may increase because its objectives are broadened, or because it is elaborated. In the first case, the number of parameters usually increases and the sensitivity of the model behaviour to each parameter decreases. Elaborating the model of a system implies the formulation of more structure. A thorough knowledge of a complex real world system, and thus a large model of it, is always required before the model can be summarized reliably for use by others. The simpler a dynamic model that still accomplishes it purpose, the better it is for instruction and for those who want to apply it in other fields or higher up in the model hierarchy. Hence, the model attains its maximal scientific value while it is being elaborated, while its value for application increases during subsequent summarization.

1.3.6 Evaluation of models

The first thorough test of a model is often the comparison of its behaviour with that observed of the real system in an analogous situation. This behaviour includes, for instance, the general shape of the time course of variables, the presence of discontinuities and the qualitative sensitivity of output to parameter values. However one should be aware that aspects of model behaviour that seem counter-intuitive at first sometimes turn out to be realistic. If the behaviour of the model matches qualitatively that of the real world system, a quantitative comparison and an evaluation of the predictive success of the model should be made. At this stage, statistical tools can be useful. But even when sufficient and accurate data are available, a model cannot be proven to be correct. Sometimes, model behaviour can be falsified, and thus one or more model components may be shown to be in error; a model cannot be proven to be incorrect as a whole. Calibration of a model, the adjustment of some parameters such that model behaviour matches one set of real world data, is a very restricted form of evaluation. Extensive calibration degrades simulation into curve fitting. Behavioural analysis is a useful form of sensitivity analysis. Innis (1978) presents some good examples. Sensitivity analysis is done by increasing or decreasing one parameter value over a broad range, and comparing direction and shape of the output with the known or expected direction.

Large-system simulation models have been developed by various groups. The evaluation of such models is difficult because many detailed observations are needed before a critical overall test can be made. It was found that if such observations are available before the final tests of a model are performed, some of the information is often, unintentionally, used for 'tuning' some parameter values. It is almost impossible to avoid this, particularly in early stages of the modelling effort, and it should therefore be realized that the inputs of the model are then not independent of the ones with which the model is compared. It is therefore useful, but often difficult, to obtain independent data for evaluation of models from literature. When observations of the behaviour of the whole system are not available, evaluation must take place at the level of sub-systems. Evaluation of models remains often superficial as a result of too small a data base. Quite some models are only 'evaluated' by establishing a good correspondence between 'predicted' and 'observed' results, while these same observed results were used to derive constants in the model. That this is a dangerous procedure needs no further emphasis. Strong experimentation is indispensable in parallel with modelling: experimentation at the explainable level for evaluation, and at the explanatory level for further improvement (See Subsection 1.1.5).

A source of increasing concern are errors in models and in their documentation. The fundamental and most difficult errors are conceptual mistakes. Apart from these, even carefully screened simulation programs often contain simple technical errors, such as key-punching errors, dimensionally incorrect parameters and deleted variables in expressions, or deleted equations. Some of these appear when the model is used to simulate new situations, or when someone else studies the simulation program. Through vigorous evaluation, modellers should eliminate as many errors as possible before releasing the model. No guarantee, however, can be given that a model is really free of errors.

Further information about sensitivity analysis, evaluation, validation and verification can be found in articles and books by Baker & Curry (1976), van Keulen (1976), Penning de Vries (1977) and Innis (1978).