PHOTOSYNTHESIS DRIVEN CROP GROWTH MODELS FOR GREENHOUSE CULTIVATION: ADVANCES AND BOTTLE-NECKS

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Additional keywords: assimilate distribution, partitioning, photosynthesis, respiration, standardisation, quality assurance

Abstract

In recent years considerable progress has been made in modelling growth of greenhouse crops. Nevertheless, the share of research in this field compared to crop modelling in general is only a few percent. Yet, crop growth models have a great potential for greenhouse production systems, because they are characterised by a high degree of complexity, intensity and diversity. Therefore it is important that crop growth models find a wider application in research and in practice. To achieve a wider use of crop growth models in the field of greenhouse production, there is a strong need for co-operation among researchers in agriculture in general and in greenhouse horticulture in particular.

Progress has been observed in the dynamic modelling of dry matter distribution, in crop photosynthesis and in the evaluation of respiration. Furthermore, the necessary validation of models and sub-models is in progress, while model applications begin to emerge. There is a clear tendency towards a more professional attitude of modelling research and related to this, the concentration of modelling activities in specialised teams, with better tools and working methods. To stimulate use of models in research and in practice with respect to protected cultivation, quality, standardisation, portability and flexibility of models remain a matter of concern.

1. Introduction

Following the successful application of systems analysis and simulation by engineers, crop growth models have also been introduced in agricultural sciences (De Wit, 1982). Initially their use was restricted to a few individuals with the required skills in computer science and mathematics as well as sufficient background in plant physiology and micro meteorology. Moreover, they needed the mentality to cope with the complexity of biological systems. Gradually a tradition has been built up over the last decades, where in more and more places, crop growth models became an accepted research tool and are even incorporated in university curricula (e.g. MSc programme "Crop Science" at Wageningen Agricultural University, The Netherlands). Certainly also the developments in computer technology and the availability of well tested and documented models of an increasing number of crops contributed to the establishment of a true discipline within agricultural sciences (Rabbinge *et al.*, 1990).

Crop modelling is a potentially very important tool for the agricultural sciences, where synthesis of knowledge is a key issue. Traditionally, agricultural science has to rely heavily upon empirical knowledge, which, by its nature, tends to be strongly linked with specific crops, locations, procedures and methods and therefore is difficult to extrapolate. Crop growth models, based upon understanding of the underlying processes, help to reuse scientific knowledge. They enable extrapolation to other crops, locations and conditions and hence to generalise knowledge. Therefore they contribute considerably to

Proc. Int. Workshop on Greenhouse Crop Models
Ed. R.U. Larsen
Acta Hort. 417 ISHS 1996

the evolution of agricultural sciences. Moreover, they support the design of new production systems based on scientific knowledge, as is customary in the technical sciences.

In greenhouse cultivation the importance of crop growth modelling should be emphasized in particular. Greenhouse production systems are managed intensively, characterised by interactions between crop, greenhouse and control system, and by control at quite different time scales, depending on the processes involved, minutes, hours, days, months, or even years. Moreover, the dynamics of the market affect greenhouse production systems strongly. Greenhouse production systems are also knowledge intensive (high level of control: root environment, aerial environment, role of crop management), characterised by a great diversity in crops and crop varieties and faced with broadened production targets (environment, quality). Because of their complexity, intensity and diversity, greenhouse production systems could be investigated and managed more effectively with the aid of growth models.

In spite of their great potentials, systems analysis and simulation are still underdeveloped in horticultural research. The aim of the present contribution is to discuss progress in crop growth models for greenhouse cultivation. The focus will be on photosynthesis driven crop models. Another category of crop models, mainly used with ornamentals, is dealing primarily with developmental processes and with morphogenesis, without explicitly referring to crop photosynthesis. This category is discussed by Lieth (1997), elsewhere in this issue.

2. Analysis

Crop growth models are of increasing importance within agricultural sciences. To give an idea of the relative significance of crop modelling in greenhouse cultivation a rough survey was made within the CAB Abstract database (CAB International) (Table 1). References dealing with crop models in relation to green- or glasshouses represent only a very small. though increasing proportion of the total number of references on crop modelling.

Table 1. Number of references over two 7-year periods dealing with [crop], [crop .and.model] and the number of references dealing with [crop .and. model .and. [greenhouse.or. glasshouse]] in the CAB Abstract database (CAB International).

Period	crop	crop .AND. model	crop .AND. model .AND. (green- .OR. glasshouse)
1979-1986	70377	2865	62 (2%)
1987-1994	91649	5090	191 (4%)

It may be questioned what the consequences are of the relatively small share of greenhouse research in overall published research regarding crop growth modelling. If it would be possible to build directly upon the expertise obtained in agriculture, this discrepancy would be no point of concern. There are, however, good reasons why research on greenhouse crop models takes a special position as compared to crop modelling in general:

- the large variation in crops and crop varieties, particularly in ornamental horticulture, prohibit the development of special models for each crop. More generic crop models are therefore required, that could be used to describe a range of crops

- the advanced control possibilities (in particular diurnal control) of temperature, humidity, and CO_2 content of the air, of water potential, chemical composition and temperature of the root environment, the use of supplementary lighting, day length control and biological control of pests, and the cost of these inputs, require an accurate evaluation of their effects on production

- the importance of indeterminately growing crops in greenhouse production, requires models that are able to handle dynamic distribution patterns

- the quality attributes (e.g. ornamental value, shape, colour, vase/shelf life, taste, etc.) of greenhouse crops represent aspects that are not covered by general crop growth models

- the high water content of many greenhouse products may affect the ability of photosynthesis driven models to predict production correctly

- year around cultivation with a high biomass per unit area in the winter season (low light) may lead to a dominating role of maintenance respiration

These characteristics justify efforts to develop crop growth models especially for greenhouse cultivation.

In the early days of crop modelling, this was mostly an activity of individual researchers albeit in close conjunction with agronomists and crop physiologists. However, with the advance of this discipline, efforts of individuals seem to be deemed to become ephemera, if not joint with a team, because of the inherent complexity of biological systems and time needed to develop correct, well designed and well validated programmes. Because the effort required to build a research group for crop growth modelling is substantial, it is not a surprise that there are only a few dealing with greenhouse crops. Most teams dealing with growth models of greenhouse crops have developed as specialisations within agricultural modelling groups. The only obvious exception to this rule we are aware of, is the modelling group of the Glasshouse Crops Research Institute (at present: HRI, Horticultural Research International, Wellesbourne, UK) at Littlehampton, UK, that took a leading position under the guidance of Dr. Warren Wilson, with internationally distinguished modellers (Thornley, 1976, 1984; Charles-Edwards, 1981, 1982; Rose & Charles-Edwards, 1981). Their performance was largely enhanced by the concentration of researchers with a good quantitative background, together with scientists with an interest in whole plant physiology, stimulated to work together. They were the first team modelling growth of greenhouse crops. Very unfortunately, their role has diminished as result of continuous reorganisations over the last two decades.

Other relevant (in terms of continuity, development and innovation) research groups working on photosynthesis driven growth models for greenhouse crops are those from Canada (Laval University, Quebec), France (INRA-Bioclimatology, Avignon), Israel (Volcani Institute, Habsor, Bet Dagan), The Netherlands (Wageningen Agricultural University; DLO-Research Institute for Agrobiology and Soil Fertility, Wageningen) and USA (University of California, Davis; University of Florida, Gainsville). The teams of Wageningen and the Volcani Institute can be considered as building directly upon the framework developed by the team of De Wit (SUCROS, Spitters *et al.*, 1989), the teams of Avignon and Florida, in turn, for their horticultural models, largely built upon the work of Dayan (TOMGRO, Dayan *et al.*, 1993a, 1993b) and therefore indirectly on that of De Wit, though both groups contributed considerably at further development of TOMGRO. For Laval and California lines of inheritance are more diffuse. All teams mentioned are characterised by a combination of experimental work with modelling activities, usually performed by a team and in most cases directly, or indirectly linked up with other activities dedicated to agriculture.

In conclusion, there are good arguments that justify a distinct line of research to develop crop models that meet the special requirements for greenhouse cultivation. For reasons of scale and critical mass, however, they generally need to be linked up, internationally with other similar groups, to share the overhead of maintaining up-to-date tools, and locally, with teams dedicated to agriculture. We will come back to the problem of cooperation among modellers and first consider the most important advances and bottle-necks in photosynthesis driven crop models.

3. Advances and bottle-necks

3.1. System borders & boundary conditions

Rabbinge (1993) distinguishes three levels of production: (i) potential, (ii) attainable and (iii) actual production, where (i) radiation and temperature, (ii) minerals and water, and (iii) weeds, pests and diseases, respectively, are the dominant limiting factors. These levels, implicitly, represent different views with different system borders: (i) the crop, (ii)the crop and the soil and (iii) the crop in interaction with the soil and with the populations of weeds, pests and diseases.

Also in systems dealing with greenhouse cultivation, different views with different system borders may be distinguished, albeit according to somewhat different criteria:

i. the crop, with radiation at the top of the canopy, CO_2 concentration and temperature of the greenhouse air as boundary conditions. It should be noted that these factors, unlike the weather in production systems in the open, are directly affected by the activity of the crop, the grower, the greenhouse characteristics and its control. In many cases it is therefore desirable to include also the interactions with the greenhouse in the system.

ii. greenhouse + crop system, where the weather and the control system (the actuators, e.g. temperature of the heating pipes, the opening of the ventilators or the rate of ventilation) are the boundary conditions.

iii. root environment, where processes related to the mineral and water supply are usually considered, but where also oxygen supply and the role of temperature may be of interest. Obviously, modelling of these processes only makes sense if the crop model describes the effect on crop growth, development and production.

iv. growth and development of populations of pests, diseases and weeds. The first category is of particular interest, because of the role of biological control in greenhouse cultivation, where also the dynamics of and interaction with natural enemies may be of interest (e.g. Van Roermund, 1995).

The systems of category (i) or (ii) may be combined with sub-system (iii) and/or (iv), depending on the problem considered. Further scaling-up may be desirable when also the role of labour, or the market are of interest within the framework of the problem under consideration. Even with respect to decisions, traditionally considered as typical horticultural decisions, such relations may be quite relevant, as for example with spacing of potplants (Leutscher & Vogelezang, 1990), or retaining extra shoots in tomato (Leutscher *et al.*, 1996).

In this contribution we will focus on systems of category (I), because they represent the core of photosynthesis driven crop growth models. Yet it is clear, that in many cases, depending on the purpose of the model, these models have to be incorporated into systems of higher complexity, to handle many of the issues in greenhouse cultivation.

3.2. Yield

The basis in all photosynthesis driven crop growth and production models is the following relationship:

$$Y_h(t) = C_f(f_{hp}/\, f_{dm,hp}) \sum (P_g - R_m)$$

where: $Y_h(t)$ is the increase in fresh weight (g) of the harvestable product at day t, f_{hp} = ratio of dry weight increase in harvestable dry matter over total dry weight increase, $f_{dm,hp}$ = dry matter content of the harvestable product, C_f = production value, defined as $W_{product} / W_{substr}$, with $W_{product}$ = the structural dry weight formed at the expense of an amount of W_{substr} (g CH_2O), P_g = daily gross crop photosynthesis (g CH_2O) and R_m = daily maintenance respiration (g CH_2O, with $R_m \leq P_g$)

In this interpretation of crop production, priority is given at maintenance respiration: only when this need is satisfied, carbohydrates are available for growth. The production value, C_f, often is erroneously interpreted as a term reflecting the loss due to growth respiration (R_g). It should, however, be noticed that it is ***not*** just $(P_g - R_g)/P_g$, where R_g = growth respiration (CH_2O equivalent weight). In the definition of C_f the chemical composition of the substrate and end product also play a role. A second common misconception is the suggestion that variations in the dry matter content in the harvestable product $f_{dm,hp}$ would be relatively unimportant, because the percentage dry matter in many horticultural products is relatively small compared to agricultural crops. In tomato fruits, a common value for fdm,hp is 5.5% (De Koning, 1994). A “small” variation of $f_{dm,hp}$ by only 0.5% represents a variation of 9% in the amount produced, at equal dry matter production.

In the next paragraphs we will consider advances and bottle-necks in each of the components of this basic equation.

3.3. Gross photosynthesis P_g

Although crop photosynthesis, generally spoken, represents an aspect of this category of crop models that is most intensively investigated, there is still considerable progress taking place. Obviously this is important, because photosynthesis represents the core of this category of models.

Most important is the progress made over the last 5 years with respect to validation (e.g. Tchamitchian and Longuenesse, 1991; Heuvelink, 1996). There are three main issues, the correct description and parametrisation of leaf photosynthesis as related to environmental factors, scaling up of photosynthesis of leaves to the level of crops and the question whether photosynthesis is affected by the balance between sink and source.

A general problem is, how to handle the variations in leaf photosynthesis among crops and varieties and within canopies. There is a large body of experimental results described in literature, demonstrating the problem. A factor that should be taken into consideration when comparing photosynthetic properties of leaves is the way how parameters are derived from the measurements. The value of the two parameters, light use efficiency (LUE) and maximum photosynthesis (PMAX), can be obtained by fitting measuring points of the photosynthesis-light relationship to a mathematical description or they may be obtained by estimation by the eye. The values obtained depend on the method and on the equation selected. Moreover, the range of the data considered also affects these values.

Furthermore, it should be realised that, in spite of commercially available, highly sophisticated equipment for measuring leaf photosynthesis, accurate establishment of the photosynthesis-light response curve is still very sensitive to proper experimental procedures, including calibration of sensors and proper conditioning of plant material. Therefore it is likely that part of the variation in photosynthetic parameters encountered in literature should be attributed to the experimental procedures.

We believe that in many cases the use of standard values for the two parameters describing the photosynthesis-light response curve may be preferable to values obtained experimentally. For C-3 crops, the majority of greenhouse crops, LUE represents the most stable property, provided that the absorption coefficient of leaves is taken into consideration. PMAX is the most plastic parameter, but its effect on crop photosynthesis is much smaller than that of LUE (Heuvelink and Bertin, 1993). Therefore, in general, the influence of a reduction in PMAX with partial leaf area index (i.e. depth in the canopy), resulting from the frequently reported decreased PMAX with leaf age or leaves adapted to low light intensity (e.g. Besford *et.al.*, 1990; Hurd and Sheard, 1981), is small (Fig. 1). Only at high light intensity combined with a low leaf area index relevant reductions in crop photosynthesis were found. Hence, in general, it is not necessary to take differences in PMAX among leaves in a canopy into account.

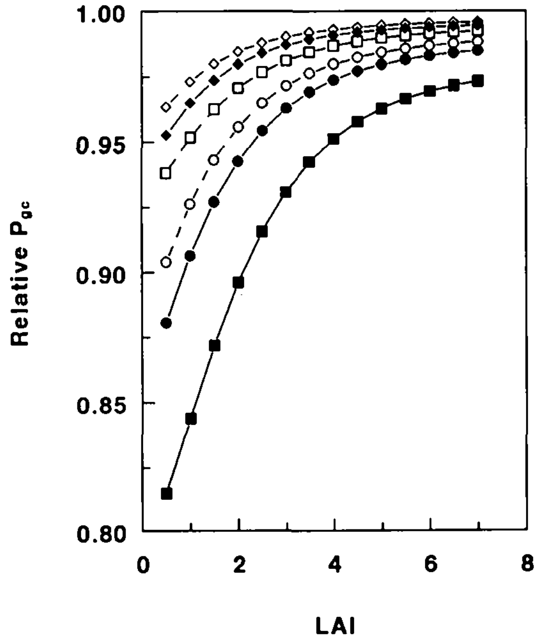

Figure 1. Simulated crop gross photosynthesis (P_{gc}) with PMAX linearly decreasing by 50% with LAI, relative to simulated P_{gc} with constant PMAX for all leaves, plotted against LAI. Calculations at 230 (♦,◊), 700 (●,O)and 1380 (■,□) μmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) and at CO_2 concentrations of 350 (♦,●,■) and 1000 (◊,O,□) μmol mol^{-1} (after Heuvelink, 1996) .

It should be noticed that the effect of CO_2 is not only on PMAX, but that also LUE is sensitive, due to the role of photo-respiration in C-3 crops, and because CO_2 suppresses photorespiration .

A negative response of photosynthesis to decreased demand for assimilates or vice versa have been reported many times (reviewed by Gifford and Evans, 1981). However, results for cucumber (Marcelis, 1991) and tomato (Heuvelink and Buiskool, 1995) clearly show that a negative influence of too low sink strength on leaf photosynthetic rate is only observed in extreme cases, which have no meaning for actual cropping systems. Marcelis (1991), for example, observed only a reduction in photosynthetic rate when all cucumber fruits where removed from the plant. We therefore believe that, in general, it is not necessary to include effects of sink demand on leaf photosynthesis in greenhouse crop models in near to optimum conditions, characteristic for intensively managed greenhouse production systems.

3.4. Maintenance respiration R_m

Maintenance respiration cannot be measured directly and is in general not well quantified experimentally. Present models dealing with maintenance respiration are essentially descriptive. As indicated before, maintenance respiration in greenhouse production deserves special attention. For example, Heuvelink (1995a) showed that for two commercially grown tomato crops a reduction in simulated maintenance respiration by 50% increased total crop dry matter production by 30%. A strong impact of maintenance respiration coefficients on predicted dry matter production of rose in winter was also shown (Kool and De Koning, 1996). The contribution of maintenance respiration to the daily carbon budget is particularly pronounced during the winter season, when daily radiation, further weakened by transmission through the greenhouse cover, is hardly sufficient to support maintenance respiration, particularly at a high biomass per unit area. The usual assumption, that maintenance respiration is proportional to the amount of biomass, would result in severe reductions in production potential for many crops at higher latitude during the winter season. Such predictions, however, are not in agreement with observed production figures of many crops in that period.

An improved estimation of maintenance respiration could be achieved by taking metabolic activity into account. De Wit *et al.* (1978) expressed maintenance respiration on the basis of protein instead of dry weight, to account for variations in metabolic activity (Amthor, 1989). Heuvelink (1995a) using relative growth rate as an indicator of metabolic activity, coupled maintenance respiration to relative growth rate by a saturation-type of response. However, for both approaches a thorough validation is missing. Both theoretical and experimental assessments of maintenance respiration rates need further improvement (Amthor, 1989). Perhaps the recent work of Bouma (1995), who established the identity and energy requirements of the most important maintenance processes, could lead to theoretically better founded models for maintenance respiration.

3.5. Production value C_f

The efficiency of conversion of assimilates into structural dry weight, according to Penning de Vries & Van Laar (1982) essentially depends on the chemical composition of the substrate and that of the end product. Quite often an approximation of 0.7 g g^{-1} derived from maize is used. Heuvelink (1995a) showed that, adopting this value, dry matter production of tomato in a large number of experiments could be predicted properly on the basis of crop photosynthesis. However, when the chemical composition of dry weight formed deviates substantially from the reference values (in particular the contents of proteins, lipids or lignins, with high assimilate requirements), conversion efficiency has to be adapted accordingly. In such case, it is important that the chemical composition of the crop is known for reliable estimates of conversion efficiency.

3.6. Harvest index F_{hp}

Only dry matter allocated to the harvestable organs contributes to yield, which makes assimilate partitioning an important factor influencing yield. Besides, for many crops, e.g. fruit vegetables, an optimum balance between vegetative (future production potential) and generative growth (short-term productivity) should be maintained. Partitioning also relates to product quality, e.g. number versus weight of individual fruits, or branching and width/height ratio in ornamentals.

Whereas crop photosynthesis is reasonably well understood and described in well validated explanatory models, this is not the case with dry matter partitioning (Evans,1990). It is generally agreed that sinks play an important role in partitioning (Gifford and Evans, 1981; Marcelis, 1996). Source strength (supply of assimilates) and the transport system from source to sink have no important direct influence on the distribution pattern (Marcelis, 1996). However, source strength may influence partitioning on the long term through its influence on the formation of new sinks (Marcelis, 1993b).

Many approaches (e.g. descriptive allometry and demand functions of sinks) have been proposed to describe the way assimilates are distributed among plant organs (Marcelis, 1993c). Often empirical models are used (e.g. distribution functions which are dependent on time or crop development stage). Such an approach may give reasonable predictions for crops like peanut or soybean, which show a determinate growth pattern (Hoogenboom *et al.*, 1990). However, in crops which grow indeterminately, like cucumber, sweet pepper and tomato, dry matter distribution changes dynamically (Hall, 1977; Liebig, 1978; De Koning, 1989; Marcelis, 1992). For such crops, the simulation of dry matter distribution based on the concept of demand functions (proposing the biomass allocation to be determined by the potential growth rates of sinks) or relative sink strengths looks promising, as has been shown for cucumber (Schapendonk and Brouwer,1984; Marcelis, 1994), peaches (Grossman and DeJong, 1994) and tomato (De Koning,1994; Heuvelink, 1995b). In cucumber, dominance of older fruits over younger ones had to be taken into account for accurate prediction of individual fruit growth (Marcelis,1994).

Although simulation of biomass allocation based on relative sink strengths is promising, problems remain in modelling organ formation (flower and/or fruit abortion; Heuvelink, 1996).

3.7. Dry matter content in harvestable product $f_{dm,hp}$

Yield (fresh weight) prediction may be disturbed by variations in dry matter content of the harvestable product. For example, in cucumber a reduction in light level from 100% to 30% reduced fruit dry matter content from 3.3 to 2.7% (Marcelis, 1993a). Dayan (pers. comm., 1995) observed under Israeli conditions even much larger variations in dry matter content of tomato fruits, varying from 4% in winter up to 8% in summer.

The relation between growth in fresh and dry matter is still only poorly understood, partly because 'the currently quite separate literatures on growth as an increase in dry matter and growth as an increase in volume -water content - are not combined (Farrar,1993). Models, in which carbon production and partitioning are combined with water up-take and transpiration (e.g. Gijzen, 1994) may be a first step in the direction of a more mechanistic model for dry matter content. Certainly more research is needed in this field. Besides its influence on yield, dry matter content of the harvestable product may also affect product quality, e.g. the taste and shelf life of tomato fruits (Verkerke *et al.*,1993).

4. Concluding remarks

4.1. Are greenhouse crop growth models at present good enough?

The question whether greenhouse crop growth models are good enough in a way maybe compared to the rhetorical question: 'When do we know enough?'. Modelling is a development process inherent to scientific research, where new insights and new knowledge are incorporated, parameters estimated, performance is evaluated and improvements implemented. Whether models are good enough depends on the user and the purpose, and, of course, on the availability of alternatives for achieving the purpose.

A researcher, using models as a research tool, generally will have sufficient experience to accommodate the programme to his needs (although it should be admitted that the effort to implement such modifications is quite often severely underestimated). Although there is always a need for more sophistication, present models are already quite useful for many research objectives, where there are hardly equivalent alternatives. They enable the user to handle complex systems and to use knowledge from other disciplines.

Programmes in which models are implemented usually represent a combination of differential equations that describe the model, with all kind of procedures, needed to activate the subroutines in which these equations are represented, in the right order, and to organise the input and the output. With increasing complexity of the model and of the cases where the models are used, these procedures tend to get more and more complex and difficult to handle and, what is worse, more specific with respect to the purpose and the user group. Consequently there is an increasing risk that users do not understand anymore the organisation of the programme and thus may not respect the programme logic. There are not yet programmes available that provide protection against such user errors, at least not in this category of general purpose programmes for research. In this respect models are not yet good enough and development in this field of research would thus greatly benefit of tools that would enable a flexible use of models, while safeguarding the internal logics of the programme.

Models have a great potential for teaching. They enable the analysis of complex systems, giving access to all kind of information that would normally not be available or only at the expense of great effort. In this way, students are engaged in active exploration and learning - an approach which is advocated in modern instructional/learning theories (DeJong, 1991). Here the accuracy of the models is of minor concern, although too obviously wrong outputs, such as impossible state or rate variables (e.g. negative weight or vapour pressure), of course, do not contribute to the confidence students have in the system. We believe that lack of knowledge is not the major shortcoming of models for teaching. Rather, the interfacing of the programmes and the complexity of the systems they describe, tend to form a bottle-neck. In our experience the use of well designed and consequently implemented graphical interfaces and the possibility to scale up and down within the complexity of the system, help to benefit of the potentials of these tools.

For growers and extension services, models generally may serve two purposes: (i) provide insight in the functioning of a system, an application that already was covered under "teaching", but where the demand for well designed interfaces may be even more imperative, (ii) a tool for decision support (DSS) and for control purposes. In the latter category two elements play a role that are of minor importance in the other applications: the accuracy of the models and the completeness. In control and DSS the function of models is to predict the performance of the system, to evaluate the effect of decisions on the performance, or to optimise the performance of a system on the basis of a performance criterion. The completeness of the model plays an important role in practical applications, because users want to get a correct answer to their question, which may generally deal with a system that is only partly described by the model. In such a case, the answer may not match with the question and hence be not satisfactory.

A model, by definition, is a simplified representation of a system, but in addition to this inherent imperfection, it should be realised that even with a perfect model we have to deal with the difficulty to describe the initial state of the system with sufficient accuracy. Furthermore, with a perfect model and proper initialisation there is still the problem that the required inputs (boundary conditions) may be difficult to know on beforehand. The most striking examples in greenhouse crop modelling are the future weather conditions and price of harvested products. The accuracy of models is thus a matter of concern, but it should be realised that the quality of decisions taken without a model also depend on proper information. Therefore, prediction errors should probably be accepted, characterised and evaluated with respect to decisions, rather than hoping for perfect models.

The inherent incompleteness of models in relation to practical questions that need to be solved, could be addressed by incorporating more user interaction in the solution methods and by accepting that answers provided by models are useful but not sufficient to solve the problem (Gollwitzer, 1991; Hofstede, 1992). In fact, arguments for such an approach to problem solving arise also from a theoretical analysis of the type of decisions in horticultural practice (P.J. Schotman, pers. comm., 1996), where it is obvious that many of these decisions could be characterised as unstructured, meaning that there is no fixed procedure to handle them.

Up till this moment there are only very few examples of models that are used in practice, demonstrating a major discrepancy between research and application in this field. We believe that models should be considered as just one of the resources of knowledge the grower or the extension officer could use and that future systems for optimisation and decision support should be able to handle these different sources simultaneously. Provided that such methods of exploiting different knowledge representations become available, present models are good enough for use in practice, although they would certainly benefit of further improvement and completion, as is the case with horticultural knowledge in general.

4.2. Organisational aspects in greenhouse crop modelling

As discussed before, we believe that it would be wise if modellers in horticulture would join forces, and would co-operate with modelling teams in agriculture. In this way it would be possible to use the modest research capacity more efficiently by using, as much as possible, existing expertise and modules in agriculture to deal with specific crops, conditions and applications in horticulture.

However, to share models and modules among horticulturists and agriculturists, and enable their use in different applications, a number of requirements have to be met. For reasons of efficiency and quality of research in horticulture we need:

1. Quality assurance

2. Standardisation (models, modules, I/O)

3. Portability (models, modules)

4. Flexibility (models/modules)

First, however, one should have the opportunity to become aware of already existing models and their specifications in an easy way. An important step forward in this field is the CAMASE register of agro-ecosystems models (a Concerted Action for the development and testing of quantitative Methods for research on Agricultural Systems and the Environment), financially supported by the European Community. The CAMASE register is a computerised and annually updated data base of model profiles, accessible through Internet (http://www.co.dlo.nl/camase). Today, about 200 model descriptions from all over the world are included in this database.

4.2.1. Quality assurance

When the user is not the designer of a module or model, and the details of theoretical backgrounds, assumptions, simplifications and limitations are not known, there is a great risk that things will go wrong. To reduce this risk, modules should be well documented. The documentation should provide information with regard to e.g. version, references where the module is described and validated, and possibly also information about the range of conditions, correctly covered by the module, and limitations in its use.

4.2.2. Standardisation

When combining different modules or models, originating from different groups and/or authors, there is a need to deal with I/O and with correct interfacing with other modules and models. The amount of work and the risk for errors is substantial if nothing is settled, and indeed standardisation in terms of formatting, use of units, proper definitions and exchange of information is indispensable.

4.2.3. Portability

If standards for interfacing, for units and definitions are set, the difficulties with respect to portability of modules among different models are not yet resolved: programmes in which models are implemented, in fact, deal with several tasks; besides the differential equations that describe the model in a strict sense, the programme also settles the internal organisation of the model, which relates to the specific context where the model is used, as well as the procedures for running the model and handling of input and output, which is specific for the application. For example, the same experiment could be simulated with measured or calculated leaf area index, CO_2 concentration or diurnal radiation pattern, requiring different procedures.

There should be a well defined task of every module and the control of the internal procedures of the programme should reside outside the module. Otherwise, modules cannot be exchanged without considering all consequences for the functioning of the programme, which is only possible for experienced users.

4.2.4. Flexibility

In the worst case one might think of specific models for each particular crop and each specific application, even if they would be based upon the same conceptual model. The consequences of this would be that a great number of models and modules would have to be kept up to date and mutually consistent with respect to new insights, improved modules and parameters. A better approach would be to build a library of general purpose modules designed such that they would serve a wide range of crops and applications. This requires an approach in writing modules such that they have a certain flexibility with respect to the specific crop or application. In practice this means that tasks should be described at a high level of abstraction, where different processes could be brought under one denominator. This is particularly true for the crop specific modules dealing with e.g. dry matter distribution and morphogenesis.

5. Conclusion

We believe that scientists working on modelling of greenhouse crops should organise themselves to develop professional tools and building blocks for common use within the international community. To achieve such an ideal, close co-operation with teams working on agricultural models would be of great benefit, since a large part of their tools and building blocks could be shared. Moreover, a more professional approach towards building and maintaining of programmes and modules is required. With the increasing use of models by an increasing range of users, having less affinity with the contents of the programmes, a heavy responsibility lays on the shoulders of model developers, to safeguard them from failures. Especially when models are going to be used in practice such errors may have serious consequences. We also believe, however, that the tools that are available now already have a great potential for horticulture in general and for horticultural sciences in particular. Horticulture is a science of integration and models provide an excellent way for synthesis of knowledge from different fields of expertise and as such opens up a completely new area for further development of research and applications in this most knowledge-intensive form of agricultural activity.

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