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Scientia Horticulturae 74 (1998) 3–20

SCIENTIA HORTICULTURÆ

Crop modelling in horticulture: state of the art

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Accepted 18 September 1997

Abstract

For the last two decades, crop modelling has become a major research tool in horticulture as in other areas of plant production. A reason for such a success is the versatility of this technique. Scientists look for conceptual frameworks, and horticulture has offered original case studies on, e.g. photosynthesis or plant architecture. Engineers want procedures to solve practical problems, and horticulture is a field where yield prediction, policy evaluation or process optimisation can be very important. Horticulture is characterised by a high diversity of cultivation systems and fruit, vegetable and ornamental species. Till now, few of them have been modelled and efforts have focused on a limited number of processes of crop growth and development. The water balance of plants, the uptake of minerals, the interaction with pests, diseases and genetics, the interplant variability, and the formation of product quality have been poorly addressed. To face the challenge of diversity, modellers will certainly have to adopt more generic approaches. For decision making, crop models should be integrated in a model of the whole system under control and connected to a model of the decision system. Even though a lot remains to be done, a major achievement of crop modelling in horticulture has been a significant increase of communication (in terms of concepts and modelling tools) in a field where the high diversity of species and cultivation systems can be an obstacle. © 1998 Elsevier Science B.V.

Keywords: Horticulture; Crop model; Fruit; Vegetable; Ornamentals; Agricultural engineering

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PII S0304-4238(98)00080-6

1. Introduction

In agriculture as in other fields, a good decision is based on a clear picture of reality. For example, irrigation is able to satisfy a crop's water needs provided its management relies on the measurement or estimation of evapotranspiration. The manager can either invest in equipment to monitor changes in water content in the soil or fluxes of water into the plant or the atmosphere, or rely on a ''schematic representation of the system'', i.e. a *model* as defined by De Wit (1970). Such a model can be based on statistics applied to a set of experimental data (e.g. Thornthwaite's formula of potential evapotranspiration, ETP) or on physical laws (e.g. Penman's formula of ETP) (Guyot, 1997). This simple example illustrates several features of modelling in agriculture that certainly explain their successes: the role of models as links between research and engineering, the interest of modelling when getting direct information from a complex system is difficult, and the availability of several approaches to modelling.

During the two last decades, horticulture did not escape developments in crop modelling. Our purpose here is to review the progress of crop modelling in the specific context of horticulture. The production of fruits, vegetables and ornamentals may require specific approaches and uses of crop modelling. Progress in crop modelling may be different in these production systems than in others. Yet, we believe that most of the questions arising from the practice of crop modelling (e.g. most of the approaches, concepts, tools and bottlenecks) are common to all fields of plant production. An evaluation of crop modelling in horticulture has to be carried out in the framework of both the specific problems of horticulture and the present status of this technique in plant production. We will address the following questions. What is expected from crop modelling in horticulture? What are the advances of crop modelling in horticulture? What are its weaknesses? How can the present bottlenecks be overcome? A rich source of information has been the activity of three working groups of the International Society for Horticultural Science namely, the ‘Computer modelling in fruit research and orchard management’ group, the ‘Modelling plant growth, environmental control and greenhouse environment’ group, and the ‘Timing field production of vegetables’ group. The outputs of the meetings they have organised reflect the trends of crop modelling in the horticultural community.

2. What is expected from crop modelling in horticulture?

Models are presented in the literature as scientific, as well as engineering tools. It does not mean that the same approaches can be used indifferently for the two purposes. The aims of a specific modelling activity should be explicit. That is why we will identify in this chapter the various motivations for modelling crops in horticulture.

2.1. The uses of models in plant production

Models offer a conceptual framework for the organisation of research. The process of building a model is analogous to working on a puzzle; the missing pieces can be identified, various persons or groups can mobilise their different skills in a cooperative project, and different levels of organisation can be considered. A good example of the efficiency of such research tools is given by the Department of Theoretical Production Ecology at the Wageningen Agricultural University that has developed, under the direction of Prof. C.T. de Wit, a comprehensive approach to modelling crop growth and development—interacting with soils, climate, pests, diseases and weeds—and overall agricultural production systems. This line of research, also carried out by other research groups, has been very effective in stimulating the scientific debate within and among different disciplines (cf. the contributions of some of the leading crop modellers in Rabbinge et al., 1990). Models are also justified, generally by the same research teams, by their applicability for improving management of the system they describe. They usually provide quantitative information from which decisions, such as crop timing, irrigation, fertilisation, crop protection, and climate control, can be taken at the field scale. On a regional scale, policies can be evaluated from estimations of potential yields, water needs, fertiliser losses, and other factors. At last, models can help scientists, engineers and growers to exchange information.

Thus, crop modelling has both scientific and operational value. If this double output indicates the richness of this technique, it may also generate contradictions. Can a model be good for both purposes or should there be two specific approaches? Penning de Vries (1982) suggested a distinction between preliminary, comprehensive and summary models. Preliminary models contain the basic features of the system. This first type of model may present some limitations due to its simplicity. Then, more insight into the processes is gained and a more comprehensive, i.e., detailed, mechanistic, model is built. At a later stage and ‘‘in order to make it more accessible to others in an intellectual and practical sense’’, simplifications may be necessary depending on the intended use of the model. In this concept of crop modelling, there are indeed various possible approaches, differing in purposes, levels of complexity and transferability, with a sequential evolution of models from a preliminary status to a comprehensive (for scientists) and a summary (for other users) status. The actual practice of modelling is much less ordered. In his study of the potential productivity of crops in Great Britain, Monteith (1977) skipped the comprehensive stage of development of models. He designed a model of biomass production in relation with climate that lumped the physiological processes of photosynthesis, respiration, and dry matter partitioning into a general coefficient for converting intercepted light into dry matter. His objective was yield prediction for policy evaluation and, with available knowledge, he *engineered* a model that fit his purpose. Passioura (1996) stressed the intrinsic difference between research and engineering models. Engineers aim at defining procedures to solve practical problems. They consider the use of models provided they give good predictions and prefer models that are simple and robust. Models are not even compulsory: rules of thumb or, more high-tech, expert-systems have proven effective in solving problems.

If a crop model is to be useful as a link between generation and transfer of knowledge, thus between research and engineering, then, from the beginning of its development, its characteristics should be appropriate to the aims of the user. Clear specifications must be defined to indicate the proper information to process and deliver. Then, the model developer should evaluate if knowledge is available to satisfy these specifications, decide on the proper time and space scales, and define the level of complexity that is needed.

2.2. Research models in horticulture

There is a specific need for research models in horticulture. As for other areas of crop production, the development of models often starts as a natural continuation of the experimental approach to a problem. ‘‘As a branch of science progresses from the qualitative to the quantitative, one day it may be expected to reach the point where the connections between theory and experiment are most efficiently made using the language of mathematics’’ (Thornley and Johnson, 1990). More specifically, because of their particular features, horticultural crops have been considered as original lab tools to study and model various plant processes. For example, greenhouse crops grown in cultivation systems in which the root and shoot environments are under a certain control offer good material for studying environmental effects on crop physiology. Significant advances in modelling leaf and canopy photosynthesis come from studies on tomato and chrysanthemum plants (Acock, 1991). The concepts of growth analysis have extensively been worked out on lettuce and tomato crops (Hunt et al., 1984; Thornley and Hurd, 1974). Fruit trees and part of the ornamental species are perennials; original modelling studies have been carried out to simulate specific phases of their development such as dormancy (Erez et al., 1990). Most horticultural species present discontinuous canopies with complex consequences on light interception, aerodynamics and gas exchange. This has justified coupled approaches integrating micrometeorology and crop physiology (Daudet and Tchamitchian, 1993; Gijzen and Goudriaan, 1989). Greenhouse crops are grown in conditions that may differ significantly from natural conditions. It is not surprising that studies on the effects of high CO_2 concentrations in the atmosphere focused on greenhouse crops before the problem of the consequences of global climatic changes arose in the eighties (Enoch and Kimball, 1986).

In all of these examples, the main objective has been the improvement of knowledge. It is clear, for example, that most of the scientific debate around the controls of photosynthesis from the chloroplast to the canopy has been organised around the design and testing of mathematical models (cf. the various contributions in Boote and Loomis, 1991).

2.3. Models for decision-making and policy analysis in horticulture

Horticulture needs crop models for a large range of applications, including yield forecast, policy analysis, and management.

The prediction of yield and its timing are important when producers have to fit closely within market or industry requirements. For example, the timing of production of field vegetables often is critical. Models of crop development enable growers to organise their planting schedule (e.g. Wolf et al., 1986 on tomato; Wurr et al., 1988 on lettuce; Wurr et al., 1990 on cauliflower). Similarly, the prices of cut flowers and pot plants are higher during very specific, short periods of the year (such as Valentine's day, Mothers' day, and Christmas). In addition, the market imposes precise quality standards such as the height of pot plants or the length of cut flowers. For such needs, models of crop development have been worked out to predict timing of production, height, and other features to improve management decisions aimed at meeting market demands (Adams et al., 1996; Fisher and Heins, 1996; Morisot, 1996).

Various regions of the world or within the same country compete for production of horticultural crops. There is a demand for better knowledge of their respective potential production limits in different regions. Yet, although this approach is fairly common for major field crops, it is still rare for fruits, vegetables and ornamentals. Challa and Bakker (1998) estimated in various areas of the world the potential production of greenhouse tomato crops permitted by the solar radiation limits. Such absolute potential production values have to be converted into practical potentials by taking into account limitations due to other environmental factors than radiation and to the availability of production techniques. Another worldwide concern is the effect on crop production of the climatic changes that could occur during the next decades. Some studies have dealt with horticultural crops such as vegetables (Olesen et al., 1993) and fruit trees (Atkins and Morgan, 1990).

In horticulture, problems of crop management are very diverse. Some issues are similar to the ones encountered in agriculture, such as water and nutrient supply, climate effects and crop timing; others are more specific. For example, perennial species, mostly fruit crops and ornamentals, have to maintain their ability to survive and produce; crop management must provide the conditions for maintenance of a high level of production. For this purpose, modelling the architecture of fruit trees and the relations between pruning and flower and fruit development has developed. Greenhouses, another specific cultivation system, provide a high level of control on the shoot and root environments. They can be compared to industrial production systems and the concepts of automatic control are applied. Operational and tactical levels of decision are distinguished (Fig. 1); they mobilise different models in terms of space and time scale (Van Straten and Challa, 1995).

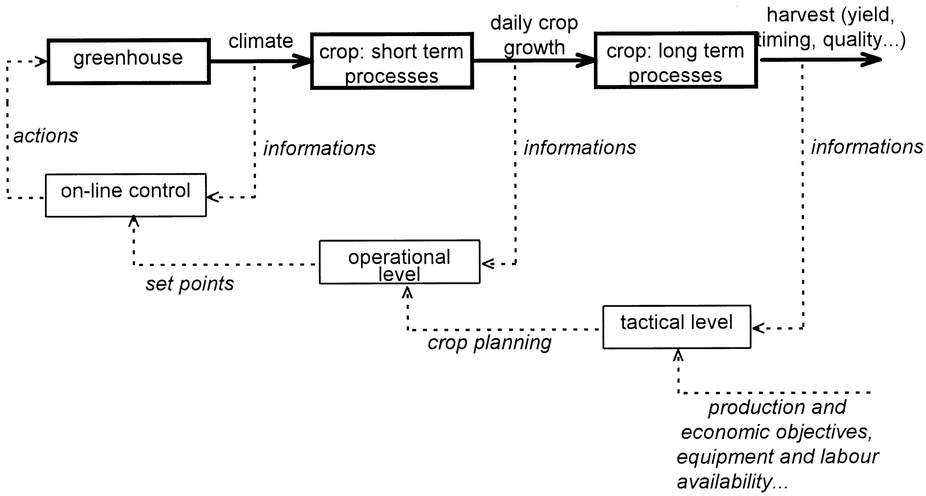

Fig. 1. A hierarchical framework for the control of greenhouse climate and crop. On-line control do not involve decision making but only set-point tracking. Crop models can be used at the operational level to simulate the short-term processes that interact with the greenhouse climate (CO_2 and water vapour exchanges) and contribute to the daily crop growth (carbon balance). At the tactical level, models are needed to relate the general policy of climate control and crop management along the crop cycle to yield formation.

2.4. Models for teaching horticulture

Models can be very useful in teaching students horticultural principles. This includes concepts on how plants respond in general to environment and management, and how horticultural species differ. In addition, models can be very useful in demonstrating interactions among processes or components of crop production systems. If students are exposed to state of the art models while they are learning concepts, they will be better prepared themselves to make progress on new developments necessary to advance science or operations management. They will begin to gain an understanding of models at an early stage in their educational process, and thus have a strong foundation from which to advance, with an appreciation for the need for interdisciplinary research for understanding the entire system (De Jong, 1991). Only a few examples exist in which models and software have been combined for teaching: PEACH describes the daily and seasonal carbon balance of peach trees (Grossman and De Jong, 1994) and SIMULSERRE simulates the production and management of greenhouse tomato crops (Gary et al., 1998).

3. The achievements of crop modelling in horticulture

3.1. A large number of species

The modelling effort in horticulture is fairly recent and it is dedicated to a large number of species. To characterise this effort, we carried out a literature search on crop modelling in horticulture by looking for a set of keywords in the titles of the references

Table 1
Number of references dealing with crop modelling in horticulture for fruit, greenhouse vegetable, field vegetable and ornamental productions (Agris database, FAO)

	Fruit	Greenhouse vegetable	Fruit vegetable	Ornamental
Period				
1975–1980	3	4	1	4
1981–1985	18	18	5	6
1986–1990	77	49	32	18
1991–1995	32	19	23	30
Topic[a]				
Growth	55	69	34	17
Development	61	10	25	33
Water balance	6	10	5	6
Nutrient uptake	8	4	4	3
Economy	8	8	2	4
Others (genetics, pathology, quality of product)	5	2	4	2

[a]Some papers may cover several topics.

of the AGRIS database (FAO, Rome): ((model* OR simul*) AND (hortic* OR fruit* OR vegetable* OR ornamental*)). After eliminating references clearly out of the scope of this review, we ended with a list of 339 references for the years 1975 to 1995. This list of references is certainly not comprehensive, but we consider it as a good sampling of available information on this topic. Its partitioning into time periods, cultivation systems and topics provides useful insight into the general trends of crop modelling in horticulture (Table 1). The story started in the mid eighties. The ratio between number of references on fruits, vegetables and ornamentals is about 2:2:1. The number of studied species is high: 25 fruit species, 23 field vegetable species, 20 ornamental species but only four greenhouse vegetable species. Apple, peach and kiwifruit represent about half of the references on modelling fruit crops, and tomato represents half of the references on modelling greenhouse vegetables. There is more variation in the modelling of field vegetables and ornamentals even though some species, such as lettuce, kohlrabi, chrysanthemum and rose, have been paid more attention.

3.2. *The dominant functions and approaches*

Priority has clearly been given to the modelling of growth and development (about 90% of the references) with more focus on development for fruits and ornamentals. Basically the approaches of modelling crop growth in horticulture have not been different from the ones developed on other crop species. Two basic frameworks have been adopted: growth analysis and photosynthesis-driven models. To study the long term accumulation of biomass along the crop cycle, plants are typically grown in various controlled conditions of light, daylength, temperature and CO_2 concentration. The dynamics of the relative growth rate (RGR, in g g^{-1} d^{-1}) is then analysed in terms of

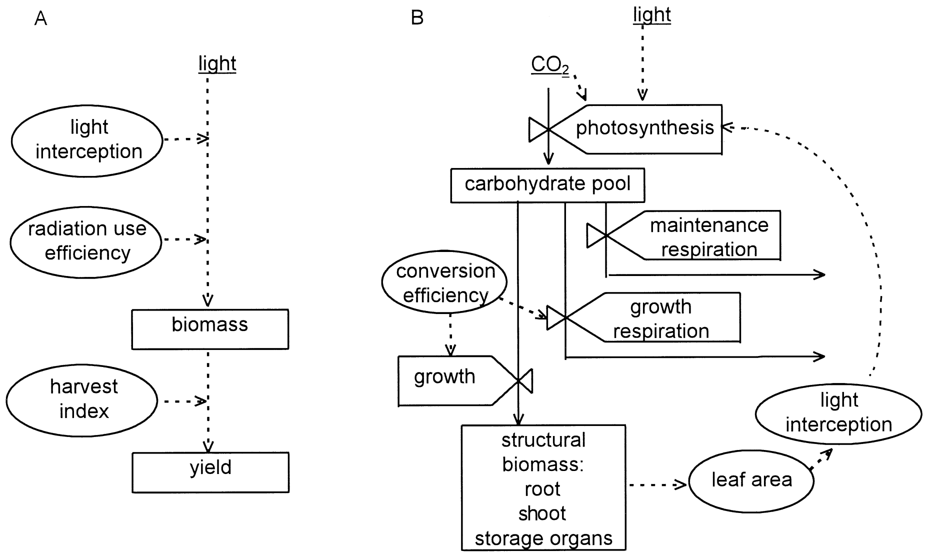

Fig. 2. Comparison of functional (A) and mechanistic (B) approaches of yield prediction (from Spitters, 1990). The functional approach describes the very basic processes that may limit yield. In model (A), the effects of CO_2 concentration or temperature have to be described through regressions with some of its parameters. In contrast, in model (B), a more realistic description is possible, provided the more numerous parameters can be estimated.

variations in the leaf area ratio (LAR, in $m^2\ g^{-1}$) and/or in the net assimilation rate (NAR, in $g\ m^{-2}\ d^{-1}$):

$$RGR = LAR \times NAR$$

i.e. in terms of changes in the size and activity of the canopy. An alternative method has been the study of the dependency of crop growth on light, through the processes of light interception and conversion into biomass (Fig. 2A). These approaches have mainly been developed in the seventies in the modelling group of the GCRI at Littlehampton (now HRI at Wellesbourne; see a discussion of the methods in Warren-Wilson et al., 1986). They can be characterised as *function-oriented* or *functional* because the intention has been to represent the key features of crop behaviour without getting into mechanisms. For example, a model of NAR implicitly covers various physiological processes: gross photosynthesis, maintenance respiration and conversion of assimilates into biomass. In the short term, environmental conditions affect these processes in different ways: light influences gross photosynthesis and not the other processes whereas temperature affect mostly maintenance respiration. To take this into account, one should either look for empirical relationships between NAR or RGR and the various climate variables (Liebig, 1989) or develop a *mechanistic* approach by describing the various processes.

The development of what has been called 'photosynthesis-driven models' has been the dominant strategy, in horticulture as well as in agriculture. These models, as reviewed by Marcelis et al. (1998), are based on a fairly detailed description of the fate of carbon in the crop, from the production to the storage and/or partitioning of photoassimilates (Fig. 2B). They can be characterised as *process-oriented*. Similar to functional models, they enable a prediction of the long-term accumulation of biomass, and they also provide the simulation of the short-term (often hourly) responses to the environment. The development of such mechanistic models has been fairly natural with herbaceous species such as tomato (Jones et al., 1991), cucumber or sweet pepper (Gijzen, 1992) for which modelling often started by borrowing concepts from studies carried out previously on field crops. Photosynthesis-driven models are also common for perennials (ornamentals such as rose; fruit trees such as peach and apple; and vines such as kiwifruit). For these species, simulations are generally carried out on a yearly basis and the plant or the branch is not treated differently from an annual (see Buwalda, 1991 for kiwifruit vines, and Grossman and De Jong, 1994 for peach trees).

The development of crops includes the appearance and ageing of organs and their spatial organisation. Organogenesis and organ ageing are often treated in a simple way. They depend mainly on temperature with no interaction with biomass production except when low source–sink ratios induce a poor fruit setting (Bertin, 1995). Most of the approaches used in modelling crop growth and development are *deterministic*: in a given context defined by the input variables, a unique output is calculated. The variability of the real system is ignored yet it is of importance in some cases. For example, if the market requires a standard product, then a reduction of variability of the marketable product becomes an objective. In a *stochastic* model, the uncertainty is part of the model. Some recent stochastic modelling attempts can be mentioned in studies of crop development: a model of flowering in kiwifruit (Agostini and Habib, 1996) and of truss appearance in tomato (Pearson et al., 1996) and a model to simulate the fruit size distribution at harvest (Hall and Gandar, 1996).

Plant morphology is often considered as an input to crop models to simulate light interception and photosynthesis. For example, when Gijzen and Goudriaan (1989) explored the consequences of the row organisation of canopies, they gave standard shapes to the plants. Morphogenesis, i.e. the dynamics of the spatial organisation of the shoot and root systems is the main characteristic addressed on fruit trees until now. In this field, the concern of horticulturists is not only light interception but also an approach to characterise the variability of flowering, fruit setting and growth in the shoot network. Underground, the ability of the root system to explore the soil as an heterogeneous medium can be determinant for water and nutrient uptake. Methodologies have been proposed to acquire data (Smith and Curtis, 1996) and codify them (Godin and Costes, 1996). The L-system approach (Prusinkiewicz, 1998), first developed on forest trees, is now diffusing in horticulture.

3.3. The other functions and approaches

The water balance of crops comprises four components: water uptake, transpiration, storage and growth. It has often been reduced to only one component: transpiration. Classical approaches (see Section 1) can easily be adopted for canopies of horticultural crops. They provide the basic information needed for irrigation management. The interactions between water availability, stomatal conductance, and gas (CO_2 *and* water vapour) exchanges have also been extensively explored (Gijzen, 1995). Recently, more focus has been given to the other components of the water balance: storage and growth. In fruit trees, evidence has shown the existence of a buffer compartment in stems (Simmoneau et al., 1993) and the relations between the dynamics of this buffer and the flow of water to the fruits has been modelled (Génard and Huguet, 1996). This is of importance in the case of fleshy fruits. There is clearly an evolution from a *functional* approach which considers only transpiration to a *mechanistic* description of all the components of the water balance (Jones and Tardieu, 1998).

The uptake and fate of nutrients in the plant is still underrepresented among modelling studies in horticulture (Le Bot et al., 1998). Attention has focused on nitrogen and most approaches have been *functional*. Habib et al. (1989) simulated the partitioning of nitrogen among classes of organs in young fruit trees in relation with the pattern of dry matter partitioning. Le Bot et al. (1997) validated the law of dilution of nitrogen in biomass (i.e. a decrease in nitrogen content with an increase in biomass) on tomato crops whereas Dapoigny et al. (1996) focused on the relation between relative growth rate and nitrogen content in lettuce. *Mechanistic* models of nitrogen balance are still in their infancies: the integration of the processes of nitrogen uptake, transport, storage, assimilation and partitioning in relation with the availability of energy and the demand of organs is poorly understood.

Few publications deal with the interactions between crops and pests or diseases in horticulture. A recent example is the work of Blaise et al. (1996) who linked a vine growth model with a downy mildew epidemic model in the following way: The infection reduced the active leaf area and consequently the assimilate production. This does not mean that the forecast and management of pests and diseases have been ignored but their modelling has been carried out independently from crop modelling. The phenology and population dynamics of insects have been modelled, particularly in orchards (e.g. Lischke, 1992). They are generally related with climate (temperature, air humidity) and crop development stage. Yet generic approaches have been developed to link various types of pest damage to agricultural crop models (Boote et al., 1996; Batchelor et al., 1993), and could be extended to horticultural crop models. The implementation of this knowledge in decision-making systems has been done through expert-systems (e.g. Rajotte et al., 1992). This formalisation of the crop–pest–pathogen system is *heuristic*; it links a set of empirical rules that give a representation of the system that is good enough for decision-making.

Genetics is another field where the involvement of crop modellers is still weak in horticulture. Yet in field crops, there are several examples of profitable interactions between crop modelling and genetic improvement. On soybean and cotton, the multiple effects of varying the leaf photosynthetic potential or the duration of the seed-filling period could be balanced and the sensitivity of the crop yield to changes in genetic parameters was evaluated (Boote et al., 1996; Whisler et al., 1986). There would be interest in increasing the interaction between genetics and crop modelling in horticulture. For example, Giniger et al. (1988) designed a specific crop model for single truss tomato crops. The comparison of such new ideotypes with classical ones could certainly be better carried out with a general tomato crop model in which the architecture could be parameterised.

4. Bottlenecks and promises

This short review shows that crop modellers in horticulture have been able during the last two decades to mobilise various modelling concepts and approaches to achieve their specific aims. Some fields have been extensively explored, others much less. Some approaches have been preferred to others. In the context of the next years, what are the challenges horticulture will have to face and what will be the priorities? The market and the public policies in agriculture will determine constraints: in a few words, farmers will have to increase the safety (for the consumers and for the environment) of their products and optimise their production systems in a competitive market. There is no indication that the public policies in research will increase the funding of agricultural R&D institutions. Thus research will certainly have to define priorities and look for efficiency in the generation of knowledge and know-how. Will models help? We will address here some of the challenges that researchers will face.

4.1. How to face the diversity of species in horticulture?

Many years of model development and testing have been dedicated to the major crop species. It will not be possible to mobilise the same energy for all species. Yet, in horticulture more than in other domains of plant production, various species may be cultivated in the same farm, especially in vegetable and ornamental production. Progress in the optimisation of such cropping systems may need the modelling of different species. Furthermore, diversification introduces new species that may become of economic importance. Fortunately, the basic features of biomass production are the same for all crops. For example, the characteristics of the three different photosynthetic metabolisms (C3, C4, CAM) are clearly identified. In contrast, development and dry matter partitioning are species-specific. Yet typologies can be defined in order to limit the number of case studies. For example, Fleury (1994) listed a number of criteria that would be relevant to build a typology in terms of yield formation: harvest during the vegetative/reproductive period, internode elongation (yes/no), determined/undetermined development, storage in fruit/grain/tuber, annual/perennial.

On this basis, it should be possible to build generic models. Their structure should be modular enough to enable the user to parameterise a range of species. Acock and Reynolds (1990) have advocated a generic structure for plant growth models. Each elemental module should involve one scientific discipline only; changes in one module should not necessitate extra work on the other modules; the input and output variables should be limited in number; they should be measurable in order to be able to test each module separately. Many benefits are expected: clarity, easier diagnosis of errors, possibility of exchanging code, easier maintenance, and reusability of modules to model new species.

To some extent, this generic approach is being used to model different agricultural crop species. For example, the CROPGRO model (Hoogenboom et al., 1993; Boote et al., 1998) was designed to simulate different grain legume crops simply by providing data files with characteristics for each species to be simulated. The same computer code now simulates soybean, peanut, and common dry bean crops, depending on which species file is selected when the model is run. Recently, Scholberg et al. (1996) demonstrated that this generic approach could be extended to model field tomato growth and yield. In this case, the development of the new model required knowledge of the processes, functions, and approaches used in the generic CROPGRO model, and a combination of literature review and new experiments were then used to quantify the numerous model parameters for tomato. No programming was required. Although this approach represents progress toward dealing with diversity of horticultural crops, it falls short of the modular approach suggested by Acock and Reynolds (1990). Modular programming approaches, such as that suggested by Van Kraalingen (1995), and new object-oriented programming languages (Gauthier and Zekki, 1996) are expected to help greatly in future efforts aiming to develop modular, generic crop models.

A more pragmatic vision consists in avoiding redundancy and favouring exchanges through the design of standards for the input and output formats of the models. For example, the DSSAT (Decision Support System for Agrotechnology Transfer) project (Tsuji et al., 1994) that has pooled a set of field crop models under a common interface has facilitated the exchange of models and experimental data. The inaccuracies in model simulations may come from the structure of the model itself or from inaccuracies in the estimation of the parameters or in the record of input data (Penning de Vries and Spitters, 1990). In the two latter cases, the availability of good experimental data is essential and any progress in the exchange of standardised data would improve both the efficiency of crop modelling and the predictive quality of models. The definition of morphological types and the adoption of some standards are necessary conditions for the development of modelling the diversity of horticultural species.

4.2. How to deal with heterogeneity?

We have seen that most published crop models are deterministic. In practice, they simulate the behaviour of a virtual *mean* plant. This conceptual approach can easily be accepted for a wheat crop sown at a high density; is it still correct for horticultural crops when the planting density is much lower? Heterogeneity may originate from the interplant genetic variability of the crop, from the variability of the shoot and root environment or from the plant management (e.g. pruning and staking). If the temporal and spatial homogeneity of the product has a price on the market (e.g. for pot plants) and/or the heterogeneity has a cost (e.g. through consequences on the organisation of tasks), then understanding and mastering the sources of variability are of importance. We have seen that stochastic models are still rare because of various difficulties. Working with variability requires more experimental effort than working on mean values. Stochastic models are generally non-mechanistic; they are based on probability density functions. Introducing uncertainty around all the parameters of a mechanistic model would certainly lead to unrealistic noise, because living systems contain homeostatic regulations that dampen variations (Loomis et al., 1979). If the genetic variability is hard to tackle, a first step is to better characterise the variability of the environment. Spatial variability of the soil has been shown to create large variations in crop growth and development, with consequences on the yield and quality of products as well as on the environment (e.g. De Tourdonnet and Roger-Estrade, 1997 on lettuce grown under plastic tunnels). New farming techniques are being developed to measure spatial variability in crops and to differentially manage fields to reduce yield variability and optimise crop management. Deterministic crop models, when combined with spatially variable environment information, have potential for developing more precise farming practices.

4.3. What about quality?

If quality is now the compulsory motto of every advertising campaign for horticultural products and hence a component of their price, it is still absent from most crop models. There are various dimensions of quality, such as shape, colour, taste, composition, and shelf-life. One simple dimension of quality that can be predicted is the mean weight of harvested organs, provided the mass and number can be predicted. But in the case of fleshy fruits their weight is determined by fluxes of water as well as translocation of assimilates. Furthermore, the dry matter content can be a component of quality: for tomatoes, it is correlated with the sugar content (estimated by refractometry) and enters into the price paid by the processing industry. A model of water import to the fruit has been designed (Bussières, 1994). At the whole plant scale, recent studies tend to improve models of water balance, including its partitioning between transpiring and non-transpiring organs. For greenhouse tomato crops, Van Ieperen (1996) studied the relations between the salinity of the nutrient solution and the dry matter content of fruits. Génard and Souty (1996) went a step further on peach fruits. They designed a compartment model that simulated the time-courses of various carbohydrate contents (among which were sucrose, glucose, fructose and sorbitol) during fruit development. These innovative examples open the way to a more complete vision of the partitioning of dry matter and water among and within organs. The main limitation is that, at present, a clear system analysis at the organ or whole-plant scales of biochemical processes other than photosynthesis is missing.

In the case of ornamentals, the quality of products is often more linked to the shape and colour than to the weight. The modelling of morphogenesis should develop, not only in terms of organ number and dimension, but also in terms of the spatial arrangement of organ units. De Reffye et al. (1988) have implemented in powerful and user-friendly softwares the concepts of plant architecture. These concepts have been first applied to trees and used in the design of landscapes. Botanists already have defined types of plant architectures, which gives generality to the approach.

4.4. Interactions between modelling and decision-making

In the first part of this paper, we stated that when management is the motivation for modelling, then it imposes some constraints. Let us consider some examples. In the case of the orchard management expert-system we already mentioned (Rajotte et al., 1992), most of the information is qualitative. For example, the disease potential levels are: none, low, moderate, high and severe. These levels depend on characteristics of the orchard given by the user, on the climate and on the schedule of fungicide application. Another example is an expert-system designed to decide every day the best temperature set-points for greenhouse tomato crops (Martin-Clouaire et al., 1993). Again, there is no modelling of either the greenhouse climate or the crop responses. The software considers a set of constraints (about crop timing, disease control, energy use, etc.), a diagnosis of the user about the vigour of the crop, and the weather forecast. In these two examples, what has been modelled is not the physical system itself but rather the decision system that is structured in decision trees. The simulation of the system is actually not needed as the user inputs information about the system. This stresses the fact that simulating the system to manage is not enough; it is not even compulsory. Both the physical and decision system have to be considered in the design of a decision-making system.

Decisions can also be based on an optimisation process. The techniques of optimal control have recently been used for the climate control of greenhouses (Tchamitchian et al., 1993). Contrary to artificial intelligence methods discussed above, the optimisation procedures need quantitative models. But these models must contain a limited number of variables. Most crop models created for research are too complex and must be simplified. Models can be reduced in several ways. Tap and van Straten (1995) carried out an aggregation of the tomato crop model of De Koning (1994) by reducing the number of state variables from 364 to 5. The aggregation was based on reasoning. Another method would have been the generation of data by the original model and the identification of a black-box model, but the rationale of the system would have been lost. A third method was the simulation of the behaviour of the original model by a neural network (Seginer and Ioslovich, 1995).

The experience of using artificial intelligence and optimal control (which belong to the tools used for building decision-making systems) put crop modelling in perspective (Martin-Clouaire et al., 1996). Crop modelling is just one step in the process of designing better management tools.

5. Conclusion

For the two last decades, crop modelling has become one of the major research tools in horticulture. We have tried to identify in this paper its advances and difficulties. Most of the efforts have focused on a limited number of species, functions (mainly growth and development) and approaches (mainly process-oriented and deterministic). To face the different situations and problems encountered in horticulture, new fields will certainly have to be explored. Diversity of species, heterogeneity, quality and decision-making are some of the present challenges. This will be possible only if cooperation among scientific disciplines develops. In terms of modelling the crop behaviour, more interaction is needed between crop physiologists and geneticists, plant pathologists, entomologists, and food technologists. In terms of designing decision support systems, specialists in agricultural engineering, farming systems and computer sciences must be involved. Having these various experts working together poses a problem of communication, and models can help building bridges. The present practice of modelling has shown crop modellers in horticulture that they actually have a lot in common, despite the high number of fruit, vegetable and ornamental species which are cultivated around the world and the high number of cultivation systems they belong to. The recurrent debates about modelling (experiments and models, simplicity vs. complexity, calibration and validation, etc.) (Passioura, 1973; Monteith, 1996), coming from all fields of plant production, permanently question their practice of research. Therefore models offer a good framework for integrating new disciplines.

For this integration to be effective, efforts have to be made towards a more professional practice of building and maintaining crop models (Challa and Heuvelink, 1996). Whereas the range of model users enlarges, their affinity with the content of the models decreases. We have mentioned the interest of generic models to face the diversity of crop species in horticulture. More generally, the adoption of standards (units, format of inputs/outputs, definition of variables), the production of proper documentation (full description of the model, validity field, references in which validation trials are described, limitations), and the use of procedures of software quality assurance would increase the portability of models and lower the risk of error or misuse. Such safeguards are particularly important when models are to be used in practice. The role of experts in computer science would therefore be enhanced in the research teams dedicated to crop modelling. Closely linked with scientists and engineers, they can contribute to new developments in the knowledge and management of the intensive cultivation systems that characterise horticulture.

Acknowledgements

The authors thank Michel Génard and Loïc Pagès for their comments that helped cover all the fields of horticulture.

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