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Modelling and management of fruit production: the case of tomatoes
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10.1 Introduction: the contexts of tomato production

Tomato is the most popular fruit vegetable crop: a large range of cultivars enable the production of various fruit types. These can be consumed either as fresh vegetables or as processed products. The per capita consumption is increasing: its world average was 13.4 kg/pers/year in 1997. The yearly world production in 1995 to 1999 ranged between 86 and 95 million metric tonnes per year. On average, 28% of the crop is processed.

10.1.1 Greenhouse versus field production

The double use of tomatoes (fresh and processed) has led to two major cultivation systems, one under cover and one in the field. Protected cultivation is specific to production for the fresh market. Its rationale is a gain in productivity. This goal can be achieved through application of transparent cover (plastic or glass) to reduce convective and radiative heat losses, which increases the temperature around the growing crop. Productivity can be increased by extending the production period and by reducing the number of limiting factors through a better control of the physical and biological environment of crops.

A greenhouse can comprise various types of equipment to control the environment. The temperature can be increased by heating, for example by burning natural gas, oil or coal, or by using thermal screens during the night. The temperature can be reduced by natural (vents) or forced (fans) ventilation, or by absorbing heat through evaporation of water applying cooling pads or fog systems, or by cooling the cover material by water sprinklers. The light level can be controlled with shading screens, by whitening the cover; by using roof
materials having a higher light transmission (light transmission of plastics decreases with ageing) and by applying supplementary lighting. Water vapour is released by crop transpiration. The air humidity can be decreased by ventilation, sometimes in combination with heating. It can be increased by evaporation of water using, for example, a fog system. The CO₂ concentration in the air can be increased (or maintained at normal level when greenhouses are closed and crop photosynthesis is active) by the injection of either industrial CO₂ or flue gases from the boiler. The latter option is only applicable if the flue gases are clean, for example, when the fuel is natural gas. Some of these techniques (such as supplementary light, fog system, injection of industrial CO₂) are expensive and seldom used for tomatoes. It should be noted that the transpiration of the crop itself very effectively reduces the air temperature and increases the air humidity. In this respect, a proper management of the development of the canopy is a major contributor in controlling the climate.

In soilless culture, the root environment is continuously monitored and controlled (ion concentration, pH, no soil diseases). Roots may develop either in mineral (rock wool) or organic (coco peat) substrates or directly in the nutrient solution (Nutrient Film Technique). As the substrate can be replaced (mineral substrate can be recycled and organic substrate used as soil amendment), no soil disinfection is needed. In order to limit environmental pollution, growers are now encouraged to close the fertigation systems: the drained nutrient solution is pumped, disinfected and brought back to set point by replenishing the water and the nutrients.

Finally, protected cultivation facilitates the control of pests and diseases. The use of pesticides can be reduced or suppressed thanks to biological control. For greenhouse tomato crops, some natural enemies of the most damaging pests have been identified. The development of some diseases such as Botrytis can be avoided with proper control of humidity and temperature thereby limiting condensation on the foliage.

In contrast to greenhouse cultivation systems, the field cultivation system permits much less control of the physical and biological environment. The timing of operations can be adapted to allow the crop to grow at the most favourable climate conditions. The required nutrients can be provided either in one run before plantation or several times during crop growth. If necessary, water (possibly together with nutrients) is supplied by irrigation. Plasticulture systems equipped with drip irrigation allow the highest control of water and nutrient availability: a plastic cover spread out on the soil keeps rainfall off and limits soil evaporation. There is, of course, a large range of intermediate cultivation systems between the most sophisticated glasshouse and the most basic field cultivation system. For example, significant areas of tomato crops are cultivated on soil under cover. In this particular case, growers still have some control on the climate but the conditions of water and nutrient supply are close to those encountered in the field.

Different cultivars are used for the two cultivation systems. For long-season production under greenhouses (up to one year), indeterminate (with a vine
shape) cultivars are grown with all side shoots removed. New inflorescences continuously appear. As a consequence, irrespective of the season, mature fruits can be harvested two to three times per week and delivered to the fresh market. Determinate (with a bushy shape) cultivars are preferred in the field when the growing season is short or when the pest pressure is high. These plants have a grouped flowering and fruiting. This latter characteristic makes such crops suitable for mechanical harvesting.

10.1.2 The uses of crop modelling in greenhouse and field production

All the physical and biological processes involved in both cultivation systems can be formalized in different ways to carry out simulations, make predictions, or optimize their management. In practice, the modelling effort has been proportional to the ability to control the cultivation system, that is, much higher for greenhouse than for field production. In greenhouse production, models have a much wider range of applications. Yield prediction is needed to match the market requirements. Models of the greenhouse climate and of the crop carbon, water and nutrient balances are designed for the optimization of the climate and for the control of fertigation. Simulation of crop growth and development makes it possible to evaluate policies of crop management. In field production, modelling has been more dedicated to predict harvest date, to achieve a steady supply of product to the factories (organization of plantation schedules), and to estimate water and nutrient requirements (for scheduling irrigation and fertilization).

In this chapter we will review the processes that have been described and the methods that have been used for modelling tomato crops in relation to their environment. We will then consider the various areas of application of these models in the protected and field cultivation systems. Of course, a modelling approach (see also Chapter 2) is often closely linked to a specific type of application.

10.2 Processes and methods of modelling tomato crops

The crop models presently available are based on two different approaches. On the one hand, new models appear with progressing knowledge as a mathematical formalization of observed phenomena and their related processes. Such models can be called research models. On the other hand, models can be designed to be part of procedures aimed at solving practical problems. In that case, they can be called engineering models. Research models are evaluated on their scientific value (realism). They are explanatory or process-oriented models, as the behaviour of a simulated system at a particular hierarchical level is the result of processes described at lower hierarchical levels. The engineering models are evaluated on their operational value (effectiveness). They can be more descriptive, being built from statistical relations (‘black-box’ models) or knowledge-based (heuristic models).
In the literature, the majority of publications on modelling in horticulture report work on the processes of plant growth and development. The processes of water and nutrient uptake, of quality formation, the interactions between crops and pests or fungi have received much less attention.

10.2.1 Mass and energy balances of tomato crops

**Carbon**

Basically, the production of biomass by a canopy relies on the net assimilation of atmospheric CO$_2$. The net assimilation is the balance between gross photosynthesis and respiration. It depends on the amount of available energy (light) and carbon substrate (CO$_2$), and on the ability of the canopy to intercept light and assimilate CO$_2$. In greenhouses, the assimilation of CO$_2$ is not only important for crop growth, it interacts strongly with the composition of the atmosphere. The daily consumption of carbon by a tomato canopy can be up to ten times the amount of carbon available in the greenhouse atmosphere. It must be balanced by either ventilation or CO$_2$ enrichment.

Longuenesse *et al.* and Gijzen have reviewed extensively models on photosynthesis of horticultural species at leaf and canopy levels. Experiments on tomato have often been used to develop photosynthesis models. The leaf gross photosynthesis responds to light by a saturation-type curve. Various mathematical formulations have been proposed and tested on tomato data, for example the rectangular hyperbola, the non-rectangular hyperbola and the negative exponential. Despite their slight difference in shape, all these functions include two important parameters: the maximum rate of leaf photosynthesis ($P_{\text{max}}$) and the initial (close to darkness) light use efficiency ($C_1$). $P_{\text{max}}$ increases with CO$_2$ concentration and with the conductance to CO$_2$ transfer from the atmosphere to the chloroplasts. It is limited at low and high temperatures (see examples of parameterization for tomato in Bertin and Heuvelink). Initial light use efficiency $C_1$ is positively affected by CO$_2$ concentration and negatively by temperature. The conductance to CO$_2$ transfer gets lower at low light intensity, high CO$_2$ concentration, high vapour pressure deficit (VPD) and under water stress.

Gross photosynthesis has been integrated at canopy scale in different ways. The simplest approach is to multiply the unit leaf activity by the leaf area index or by the projected leaf area ("big leaf" approach). Other models take the transmission of light in the canopy into account using an exponential law of extinction. When the leaf light response curve is a rectangular hyperbola, analytical integration at canopy scale is possible (for example, in Jones *et al.* for tomato crops). More sophisticated models provide a detailed simulation of light scattering and transmission through leaves, and of the distribution of diffuse and direct light based on a thorough description of the spatial distribution of the leaf area and leaf angle. The specific case of row crops such as tomato has been addressed and reviewed by Critten.

The respiratory efflux of CO$_2$ is significant: on a daily basis, it can represent a quarter to a half of the gross photosynthesis of a developed greenhouse tomato.
crop. Respiration of plants has been divided functionally in two components: maintenance respiration and growth respiration. Maintenance respiration corresponds to the energy needed to maintain the ionic gradients across biological membranes and the pools of macromolecules such as proteins. Growth respiration corresponds to the energy involved in the synthesis of new biomass from assimilates and minerals. Maintenance respiration is calculated as the product of the plant or organ dry weight times a maintenance coefficient. Growth respiration is calculated as the product of the plant or organ growth rate times a CO2 production factor. In crop models, maintenance and growth respiration are summed up to estimate total respiration, generally on a daily basis. Respiration rate increases exponentially with temperature. Since this conceptual framework was proposed in the late 1960s, most research has been carried out on the accuracy and determination of the parameter values. The maintenance coefficient has been related to the tissue metabolic activity. For tomato, Heuvelink has hypothesized that the maintenance coefficient decreases with ageing. The CO2 production factor is proportional to the energy cost of biomass synthesis. It varies among organs and with ageing (see Gary et al. for tomato). The modelling of plant respiration has recently been re-examined by various authors looking for more mechanistic connections between the production of respiratory energy and ongoing processes in the growing plant (biosyntheses, translocation, ion uptake, N assimilation, protein turnover, ion-gradient maintenance).

The crop carbon balance includes the carbon exchanges between the atmosphere and the canopy (net photosynthesis), and the partitioning of carbon in the plant between one or several pools of photoassimilates and the growing organs. Gent and Enoch put together simple formulations for gross photosynthesis and respiration, and provided a relation between availability of photoassimilates and growth, that is, production of the elaborate compounds of the plant tissues from the photoassimilates. With these simple formulations the 24-hour dynamics of CO2 exchanges and assimilate pool of young tomato plants can be simulated. Such a simple carbon balance model (Fig. 10.5) was reshaped for control purposes by Seginer et al.

Water
The water balance in the crop is an important crop property in various respects. Water import contributes to the plant growth, as water status influences cell extension in growing organs and water flow conveys nutrients to growing or storage organs. Water status also partly controls the stomatal conductance and may therefore affect photosynthesis. At last, the evaporation of water during transpiration is connected to the absorption of latent heat: it strongly determines the temperature of the canopy and therefore, of the air in a greenhouse.

The modelling of water relations of horticultural crops has been reviewed by Jones and Tardieu, van de Sanden and Jolliet. Research in this domain has been motivated by two main concerns:
(1) simulating the water status and its relation with various physiological functions (organ extension, stomatal opening, water flux) and
(2) simulating the water flux through the canopy to estimate the water requirements of crops.

The basic framework that has generally been adopted is an analogue of Ohm’s law: the water volume flux along a certain path is proportional to the gradient of water potential and to the inverse of a flow resistance. For tomato, van Leperen designed a model describing the pathway of water from the root environment to the atmosphere through one root compartment and three shoot layers within a vegetative plant, and the dynamics of water potential in roots, stems and leaves. Premises of modelling the water fluxes to the tomato fruit through the phloem and xylem vessels can be found in Guichard et al. These premises are based on Fishman and Génard’s model. The dominating phloem fluxes depend on the concentration of carbohydrates in the phloem vessels and on the ability of the fruit to unload these carbohydrates. The xylem flux varies with the water potential in the stem, since the fruit water potential remains fairly stable in time and in different environmental conditions. Due to a high resistance to water flux in its epidermis, the transpiration of the tomato fruit is limited. Recently, it was modelled as a function of irradiance and VPD by Leonardi et al.

At the canopy scale, the transpiration in tomato crop has been modelled applying the classical Penman-Monteith approach as the sum of a radiative component, proportional to the global radiation absorbed by the canopy, and of a convective component, proportional to the VPD. The canopy resistance to transfer water vapour comprises the aerodynamic resistance that depends on wind speed and air and leaf temperatures, and the stomatal resistance that depends on radiation, leaf air saturation deficit and leaf temperature (see, for example, Boulard et al. for tomato crops). For operational purposes, the complete analytical model has been simplified to a two-parameter formula, the parameters being either derived from the complex model or identified in situ.

Energy
A crop canopy can be compared to a solar collector. The absorbed radiation is the balance between incident, reflected and transmitted global radiation. In their study of light interception by glasshouse crops, Warren Wilson et al. measured for a tomato canopy an average reflectance of 13% and an average transmittance of 23.5% of the incident light in the photosynthetically active radiation (PAR) waveband. Light absorption was improved by about 10% when the soil was covered with a white plastic sheet. Light absorption increased also with the foliage development to almost complete with a leaf area index (LAI) of 4 or above. It is also related to plant density and row spacing as it tends to increase when the plant distribution is more uniform. The distribution of light and its absorption by rows of canopies such as tomato crops has been modelled by using several approaches (see review by Crittenden). Among these are the exponential extinction curve, and various
models that take light scattering and the distribution of diffuse and direct light, and leaf angle distribution into account. Part of the absorbed radiation is used by photosynthesis for carbon assimilation and biomass production. This proportion is estimated by the radiation use efficiency (RUE), that is, the ratio between the energy equivalent of biomass and the absorbed (or incident) global (or PAR) radiation. For a tomato crop, Aikman estimated it to be about 7% when based on the absorbed PAR or 1.6% when based on the global radiation outside the greenhouse.

A significant part of the absorbed energy is actually dissipated by the crop as latent heat by transpiration. As a consequence, the temperature of a transpiring canopy is lower than the air temperature. This difference generates a flux of sensible heat from the air to the canopy. In a greenhouse, depending on the LAI, 50 to 70% of the solar energy input is used for evapotranspiration. This justifies that the crop water requirements are estimated from the absorbed or incident global radiation.

Minerals

Nutrients are essential components of the plant tissues. Fertilization is a very basic cultivation technique to avoid any limitation of growth by the availability of minerals and to gain some control on yield and product quality. As for carbon and water, both mechanistic and black-box models have been designed (see the extensive review of Le Bot et al.). The mechanistic models are research models describing specific processes like nutrient uptake, transport and assimilation. Even for nitrogen, the most studied element, the regulation and integration of these processes at a whole-plant scale are still in discussion. For tomato, two main approaches of mechanistic modelling have been proposed. According to Le Bot et al., the time-course of nitrate uptake is related to the translocation of carbohydrates to the roots to cover the energy cost of nutrient uptake. According to Cardenas-Navarro et al., nitrate uptake is related to the maintenance of a steady internal ion concentration.

More general (black-box) models link the demand of nutrients directly to the growth rate. It has been established for several elements (nitrogen, potassium, phosphorus) that a critical concentration in plant tissues should be maintained to approach the potential growth based on total intercepted radiation. For nitrogen, this critical concentration gradually declines with the accumulation of biomass during the vegetative phase. Le Bot et al. parameterized this relation for tomato plants. To explain this decline in nitrogen content, Caloin and Yu suggested two compartments in the biomass, one mostly active for growth and having a high nitrogen content, and another dedicated to structures and storage having a lower nitrogen content. With crop development, the second compartment tends to dominate the first. This model was calibrated for a greenhouse tomato crop by Bellert et al. A comparable approach of the nitrogen demand by processing tomatoes has been implemented in the EPIC model to evaluate different fertilization policies in terms of crop growth and nitrogen dynamics in the soil.
Few models are presently available for other nutrients. Only recently, a first model simulating the flux of calcium in pepper fruit and its relation to quality, measured as the occurrence of blossom-end-rot, was reported.

10.2.2 Yield formation
Tomato has been a pioneer vegetable species for crop modelling. The formation of yield (organ appearance, dry matter production and partitioning) has been studied thoroughly and formalized with various approaches, again either empirical or mechanistic. The approach of fruit growth has been based on models of dry matter production. Water fluxes towards the fleshy tomato fruits (around 95% water) have been studied and modelled only recently.

Production of biomass
Different approaches to modelling biomass production have been developed for different crop species including tomato. In the ‘photosynthesis-driven’ models, integration of net photosynthesis and conversion of the resulting photoassimilates into biomass are used to compute the accumulation of dry matter. As already mentioned, net photosynthesis is the balance of photosynthesis minus respiration. The coefficient of conversion of assimilates into biomass depends on the energy value of the synthesized tissues. Gary et al. have estimated its ontogenetic variation for the different types of tomato organs. Challa and Bakker estimated the potential production of greenhouse crops in various regions of the world using this approach. It is also the first step in most of the tomato crop models. Bertin and Heuvelink compared the dry matter production estimated by Jones et al.’s and Heuvelink’s models.

In the RUE approach, the production of biomass is considered as a sequence of energy conversions from the incident radiation to the energy content of biomass. Interception of (photosynthetically active) incident radiation is linked to the leaf area index by a saturation type curve; the coefficient of conversion of intercepted light into biomass is higher for C4 (e.g. maize) than for C3 (e.g. tomato) species and it increases at high CO2 concentration. This approach was validated at different conditions for greenhouse tomato crops. A similar approach has been used for different species including tomato in the STICS modelling platform.

Timing of development
Development processes include the formation of new organs and their ageing and phase transitions at whole plant (e.g. vegetative vs. generative periods) or organ (e.g. fruit setting) scales. Formation and ageing of organs depend mainly on temperature, following a bell-shaped curve that can be described by the Arrhenius equation. Such a response curve has been calibrated for the formation of new leaves and trusses and for fruit development from flowering to maturity, and introduced in most tomato crop models (e.g. De Koning). Under the hypothesis that the response of development rate to temperature can be considered...
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as linear in a limited range of temperature, daily temperatures can be summed to calculate a ‘thermal time’ expressed in degree-days that is, by definition, independent of the temperature regime.\(^5\) (Tjiskens and Verdenius\(^5\) recently revisited the modelling of biological processes that depend on temperature.)

In tomato plants, fruit setting is the phase transition from flowering to fruit growth. It has been observed that the higher the source-sink ratio (that is, the fraction of the plant potential growth rate that can be covered by the current production of photoassimilates), the more successful fruit setting.\(^6\) This relation was formalized in the TOMGRO model.\(^6\) In this model, the dynamics of flowering, fruit setting and fruit ageing determines the age structure of the populations of vegetative and generative organs at any time during production.

**Dry matter partitioning**
The dry weight of harvested organs depends on the fraction of dry matter that is allocated to them. In the case of fruit species such as tomato, the vegetative-generative dry weight balance is a key component of crop models. This ratio can change with the plant development stage, and dynamically with the strength of vegetative and generative sinks. The sink strength of an organ or a group of organs is their ability to attract photoassimilates. It is the potential growth rate when no competition for carbon resources exists among organs.\(^6\) It varies with the stage of development of the organ and increases with temperature. It is not affected by the availability of assimilates themselves. Heuvelink\(^6\) demonstrated that, in tomato, the relative position of leaves and fruits on the plant does not affect dry weight ratio. In other words, all the organs of a tomato plant have the same access to the carbon resources. Consequently, (1) the vegetative-generative dry weight allocation ratio depends on the number and age structure of leaves, stem internodes and fruits, and (2) when the source activity (net photosynthesis) is lower than the sink demand, the actual growth rate of all organs is limited in the same proportions. These concepts have been implemented in the tomato crop models, designed for indeterminate cultivars. Heuvelink and Bertin\(^6\) have compared two of them. Until now, only a few attempts\(^6\) have been made to verify and validate this theory for determinate cultivars.

**Dry matter content of fruit**
Like most vegetable species, tomato fruits contain a high content of water at harvest. This water content is the result of xylem and phloem influxes and transpiration efflux during fruit growth. As mentioned earlier, the modelling of lateral fluxes within the plant (from stems to fruits) and of the fruit transpiration has only been studied quite recently. These processes will be introduced in a tomato crop model provided carbon and water fluxes can be coupled. To this end, the dynamics of water potential in the stem and of carbohydrate content in the phloem and the possible variations in water transport resistance in the fruit peduncle and epidermis have to be determined.

At present, tomato crop models are based on the assimilation and partitioning of carbon only. The dry weight of harvested fruits is calculated and converted into
fresh weight by applying a coefficient of dry matter content that is either fixed\textsuperscript{16} or variable with the season.\textsuperscript{57} In the latter case, the fruit dry matter content is higher in summer than in winter as the environmental conditions in summer tend to favour water stress (when radiation, VPD or salt concentration in the nutrient solution are high). The dry matter content of mature fruits is also genetically determined: it is generally higher in cultivars with small (cherry, cocktail) than with large fruits.

### 10.2.3 Other processes

**Quality formation**

The quality of tomato fruits covers a number of different characteristics. Which are the most important depends on the use of the products, whether for the fresh market or for the industry (Table 10.1) (see also Chapter 17). The average fruit fresh weight can be modelled based on the weight and number of harvested fruits. The fruit sink strength or potential growth rate is a genetic parameter. In tomato, it increases from cherry over cocktail cultivars to round and beefsteak cultivars. Within the range of genetically determined fruit sizes, the actual fruit grade obtained can be controlled in greenhouses by climate and crop management. Larger fruits can be obtained by increasing the source activity with, for example, CO\textsubscript{2} enrichment or by decreasing the competition for assimilates, for example by fruit pruning to a lower total fruit load. At present within the growing area, fruit grade is the only quality attribute that is properly simulated. For example, the SIMULSERRE simulator, based on the TOMGRO model, enables the evaluation of different strategies of climate and crop management in terms of yield, fruit grade, and energy and CO\textsubscript{2} consumption.\textsuperscript{66}

<table>
<thead>
<tr>
<th>Quality variable</th>
<th>Sources of variation</th>
<th>Fresh market industry</th>
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<tbody>
<tr>
<td></td>
<td>Genetics</td>
<td>Climate</td>
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<tr>
<td>Fruit grade</td>
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<td>Uniform colour</td>
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<tr>
<td>Cracking</td>
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<tr>
<td>Blossom end rot</td>
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<tr>
<td>Shelf-life</td>
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<tr>
<td>Dry matter content</td>
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<tr>
<td>Sugar content</td>
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<tr>
<td>Acid content</td>
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<tr>
<td>Aroma content</td>
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<tr>
<td>Texture</td>
<td>x</td>
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<tr>
<td>Health value (antioxidants)</td>
<td>x</td>
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Table 10.1 The quality variables of tomato fruits, their major sources of variability and their significance (* low to *** high) for the fresh market and the industry
Ongoing research is conducted on the formation of the tomato fruit quality in terms of chemical composition (sugar, acid, aroma contents), appearance (colour, cracking, blossom-end-rot) and health promoting compounds (antioxidants). For these quality variables models are still largely unavailable, although some can be related to the carbon, water or mineral fluxes to the fruit. The sugar content could be linked to the carbon availability but acid or aroma contents could not.\(^67\) The frequency of cracking of the fruit epidermis has been linked to the crop water status.\(^67\) The occurrence of blossom-end-rot has been related to the calcium flux transported by the xylem network.\(^68\)

*Interactions with pests and diseases*

Even though the effects of pests and diseases on crop behaviour is of major importance to tomato cultivation systems (especially in relation to environmental and health concerns), few simulation models of plant disease are available. Seghi *et al.*\(^69\) reviewed some empirical models that forecast diseases (*Alternaria solani, Phytophtora infestans*) in tomato crop from climatic data. The effect of disease, induced by *Septoria lycopersici*, on tomato yield was estimated. In their review on the control of *Botrytis cinerea* in greenhouse tomato, Nicot and Baille\(^70\) identified only a small number of models for greenhouse vegetables, one designed to forecast the fungus epidemics in cucumber under unheated greenhouse and another to simulate spore germination on tomato leaves. More generally, epidemiological models developed for field crop and often based on the occurrence of free water on the canopy, could be generic enough to be adapted to greenhouses. However, the development of mechanistic models on epidemiology or population dynamics in relation to the environment and crop status is a complex task. An example of a research model simulating the parasitoid-host relation between *Encarsia formosa* and the greenhouse whitefly on tomato crops was published by van Roermund *et al.*\(^71\) Such a model can be used to evaluate release strategies under various climate conditions.

### 10.3 Areas of application

One of the ideas about model application most widely shared within the crop modeller’s community (but maybe not so among scientists involved in control or management), is that crop or plant process models can readily be adapted to design control or management systems for decision support. Along with teaching, management and support are probably the two main areas of application for the models described in the previous sections of this chapter. Management can be defined as the sequence of three operations: planning, implementation and control. The planning operation sets up the strategy which encompasses the goals assigned to the cultivation and the means to achieve these goals. Implementation performs the translation from the strategy into actions, while control ensures the proper applications of these actions by constantly monitoring the process and revising the mode of application of the action.
Being a management task, crop management (and hence climate or fertigation control) requires identification and execution of suitable actions to obtain the desired crop behaviour and to reach the assigned goals. The decision process leading to the determination of the actions to be taken is a difficult task. It depends on:

- uncontrolled and uncontrollable external factors
- several complex interactions between the crop and its environment (both physical and economical)
- knowledge of the crop state.

While crop models can help to determine the crop state, models of the crop environment (not discussed so far) can also be used to clarify the state of the crop environment and to identify the interactions between the crop and its environment.

In view of these remarks, the first obvious application of crop models is as information providers, providing information that is otherwise not readily accessible to the grower, either because no measurement system is available or because the cost of obtaining the information would be prohibitive. Remarkably enough, most of the reported applications of models in the field of climate or fertigation control in greenhouses go one step further. As will be seen, models are used in optimization routines as representations of the crop processes (not of its states). This shift deserves a more detailed explanation. When using models as information providers, the interest is focused on the output, whatever the expression of the model may be. Accuracy of the results is paramount, especially when these results are predictions, that is, expected values of one or more crop states. Whether the model formulation represents the actual crop processes or not is irrelevant here. On the contrary, when models are used in optimization routines, and more specifically within the optimal control theory, the emphasis is on the formulation itself. For example, representing data with a parabola or a sine function may give numerical results which will differ little while the derivatives will be very different, and derivatives are used heavily in optimization procedures. Different expressions can lead to different control actions, which implies that the choice of the model to be used will not only depend on its accuracy in terms of prediction or simulation, but also on the actual equations that make the model. With respect to this use of models, they are process representations.

In the following subsections we present an overview of current works using models as information providers (teaching and crop management applications) and as process representations (climate and fertigation control).

10.3.1 Teaching
Crop models are interesting tools for teaching horticulture. They can fulfil different goals. They give an insight to the processes that together result in the crop behaviour. They provide a faster means than real experimentation to
demonstrate the effect of management on the crop. They can, of course, not
replace the experience one gains from observing a real crop growing. In the
SIMULSERRE project, embedded in a user-friendly interface, the TOMGRO
model was coupled to a greenhouse climate model and to a model of a simplified
greenhouse climate controller. In the virtual experimentation, the user defines
the climate control strategy (heating, ventilation, CO2 set-points) and the truss
pruning plan for the growing season. The results of these simulations are stored
in extended details (from hourly values for all matter fluxes within the plant and
between the crop and the environment to daily values of various state variables
of the crop such as LAI, fruit load, harvest, etc.). Results can be viewed and
compared with several types of plots (hourly, daily, cumulative values). For
example, CO2 enrichment policies can be compared and the differences in yield
as well as in photosynthetic fluxes can be tracked. Demonstration of the role of
key elementary processes is therefore straightforward and helps the student in
obtaining an integrated view of the crop and management.

10.3.2 Yield prediction and crop management
The demand for yield prediction varies with the tomato cultivation system. In
field production, determinate cultivars are selected to get fruits ripe for a single
harvest. The expected time of harvest and expected amount of product are
predicted to enable an integrated planning of production and processing. For
example, Wolf et al.72 estimated, the times of emergence, flowering, turning
stage and harvesting of tomatoes for processing based on the heat sums. McNeal
et al.73 went a step further and predicted the mass of fruits at harvest using a
greenhouse tomato crop model (TOMGRO) adapted to field conditions.

In greenhouse production, yield is planned for a long period of time. In
Europe, there is strong competition between the various regions of production.
In negotiations with the product buyers, growers must be able to announce their
weekly production for the next couple of months. For this purpose, a simple
tomato crop model named TOMPOUSSE was developed.51 To be useful for
practical operation, it had to respect a set of requirements:

- run with data commonly available in commercial conditions (plantation date,
duration of the crop cycle, cultivar, weekly average values of radiation,
temperature, CO2 concentration and policy of fruit pruning and stem density);
- simulate the effect of the major cultivation techniques of climate control and
crop management;
- deliver the weekly yield and average fruit weight.

Within this framework, the simplest formulations were retained in the model.
The RUE approach was adopted to simulate the production of biomass. Every
week, the dry matter allocated to fruits is partitioned among different age
groups, according to the box-car-train technique.74 The integration of fruit
growth and development permits the estimation of the weekly number and dry
weight of mature fruits. The dry weight is converted into fresh weight using a
dry matter content varying along the year. Such a simple model enabled the simulation of the time-course of production of greenhouse tomatoes in various regions and production systems (Fig. 10.1). It was also possible to estimate the effect on potential production of limiting operational factors (see previous sections).

In commercial conditions, yield forecast can be produced for the next weeks by running the model several times with weather inputs taken from a radiation database recorded in the region, and for the planned cultivation strategy (management of temperature, CO2 concentration, truss pruning, stem density). Interestingly, due to the indeterminate development of greenhouse cultivars, the variation in the short-term predicted yield is low because the possible variations in global radiation affect only the last stages of fruit development (Fig. 10.2b). Another attempt to estimate the potential production of greenhouse tomato crops has been based on the calculation of the daily crop photosynthesis in response to the available radiation depending on season and latitude. The difference between the potential and actual production in various parts of the world helps analysing the importance of different limiting factors.

Different parts of the TOMPOUSSE model reflect the different cultivation techniques. The efficiency of light interception depends on the leaf area index. Stem density and leaf pruning can affect the leaf area index. RUE increases with CO2 concentration. The dry weight allocation ratio to fruits responds with a hyperbolic curve to the fruit load per plant. The appearance and ageing of organs is strongly affected by temperature. The TOMPOUSSE model can be
used as a simulator to evaluate different strategies of crop management. In the example presented in Fig. 10.3a to d, various policies of truss pruning are evaluated with respect to the fruit grade. De Koning used a similar approach in a model of dry matter partitioning to optimize shoot density and number of fruits per plant.

These crop models, used to evaluate the biological consequences of policies of crop management, are still far from real decision support systems (DSS). For this purpose, the models should describe not only the dynamics of the crop and of its physical environment (greenhouse climate and/or soil), but also the decision-making process itself and its interactions with the biophysical system. For example, the GX/Sim system is a greenhouse simulating platform that can specify the decision rules the grower uses to adapt the climate settings to the current climate conditions.

In the CONSERTO project, a dynamic model of the greenhouse production system has been designed with three components: the decision system, the instructions-to-actions system and the biophysical system (Fig. 10.4). The decision system describes the management strategy applied over a cultivation period to realize production objectives. A management strategy consists of several conditional plans the realization of which is conditioned to the occurrence of specific events. In CONSERTO, it deals with climate and fertigation management, and manual operations such as fruit and leaf pruning, training and harvesting. A conditional plan comprises a nominal plan of instructions and a trajectory of desirable states and appropriate reactions that permits adjustments along the crop cycle. A nominal plan is a sequence of tasks assigned to a worker team.

The instructions-to-actions system converts these decisions into actions via automatons (the climate and fertigation control system) and workers. Because of

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**Fig. 10.2** Simulated potential yield of a greenhouse tomato crop based on the mean global radiation (measured in Avignon, France from 1969 to 1992) until week 1 (a) or 25 (b), and on the different 24 years (1969 to 1992) from week 2 (a) or 26 (b). Mean (—), maximum and minimum yields (—), relative variation ((max−min)/mean, ————). The variability of yield prediction is higher when carried out from the vegetative (a) than from the generative (b) phase. It stabilises at a lower level in (b) than in (a) because, in this particular region, the weekly global radiation varies less during the second half of the year.
Fig. 10.3 Simulated effect of two strategies of truss pruning on the tomato fruit grade along a crop cycle. In this example, the objective is to keep the fruit grade constant after planting mid-September in the south of France, even though global radiation (—, mean of weekly values measured in Avignon, France from 1969 to 1992) goes down in winter then up in spring. (a), (b): when the number of fruits per truss (—) and consequently the fruit load (●) vary together with the radiation level, then the fruit grade (○) varies little. (c), (d): when the number of fruits and the fruit load are not regulated, some fruits do not set (x) during the shortest days but this natural regulation is not enough to control the fruit grade.

Fig. 10.4 The greenhouse production system as formalized in CONERTO. Dotted arrows represent the information each sub-system gets from the environment whereas full arrows represent control inputs.
limited resources (e.g. workforce or capacity of the heating system), what is actually realized may not fit with what was prescribed in the framework of the nominal plan, and alarms may be raised. Information on the actual use of resources is sent back to the decision system.

The biophysical system comprises a greenhouse climate and a tomato crop model. Actions and climatic events control it. The tomato crop model is a redesigned version of TOMGRO\textsuperscript{16,61} implemented in an object-oriented framework.\textsuperscript{79} The outputs provide not only information on physical and biological performances of the system under a set of actions but also indicators (for example, the plant vigour or predictions of important events such as flowering or fruit maturity) useful for the decision system.

10.3.3 Climate control
Climate control is an operational management task which includes the activities of determining the crop and system states, choosing the set of goals to pursue within the more general set of goals defined by the strategic management of the crop and finally deciding upon which climate modifications are needed for the day at hand. Crop and greenhouse models can be useful in different ways for the grower to perform this task, either by giving an estimate of the crop state or by performing the decision task and offering a ready-to-use solution.

\textit{Models as information source}
We are aware of very few model applications in this way for tomato, although a successful application on cotton is reported.\textsuperscript{80} Attempts to provide information on diseases have also been reported for tomatoes, however, with only minor connections to the climate management problem.\textsuperscript{81,82} Finally the work of Harazono \textit{et al.}\textsuperscript{83} and Harazono\textsuperscript{84} can be mentioned: a model for photosynthesis is used to provide information to a climate control system on this difficult to monitor flux. The task of the controller (based on rule inference) is to adapt environmental conditions (temperature, humidity and CO\textsubscript{2}) to maintain an appropriate photosynthetic flux, as predicted by the model. None of these systems apply on-line parameter estimation, a technique widely used in computerized industrial process control. The goal of on-line parameter estimation is to assure that the model, through adequate parameterization, always describes the process as closely as possible.

\textit{Model-based climate control}
Our understanding of model-based climate control encompasses all the approaches where new climate set-points are determined using either information output by the model or the knowledge contained in the model itself. Within this scope most approaches are designed for the ultimate goal to control directly the greenhouse climate. However, Schotman\textsuperscript{85} argues that some of the drawbacks of such a conception of climate control are that:
the grower has no control over the objectives assigned to the control generating routine;

information needed by the model-based control system often has no agronomic or relevant meaning to the grower.

Optimal control is probably the most widely used method to exploit available models and determine ‘optimal’ crop environmental conditions. The optimal control theory, either based on Pontryagin’s minimum principle or on Bellman’s principle of optimality, develops as follows. Noting that scalars are denoted with italics and vectors with bold, let $\frac{dx}{dt} = f(x(t), u(t), p(t))$ be a dynamical model of the plant (plant is taken here in its industrial meaning of factory, the factory being in our case the crop!), where dynamical model means differential equations, $x(t)$ is the state vector of the plant, $u(t)$ is the control vector (quantities that can be manipulated to modify the plant behaviour), $p(t)$ is the perturbation (or uncontrolled) vector and $t$ denotes time. Optimizing the plant behaviour implies that an objective function $J()$ has been defined which measures how well the system performs. $J()$ is classically the sum of two terms. The first, $\Phi(x(t_f), t_f)$, denotes requirements on the end-point of the control horizon (expressed through a weighting function) which allows for optimization in time (minimum time problems where $t_f$ is let free and must be as low as possible), or for the specification of desired final state, $x(t_f)$. For example, a combined problem could be to produce lettuces of a given fresh weight in the shortest time possible so as to maximize the number of crop batches during the season. The second term in $J()$ is an integral which accounts for all running costs or gains relevant to the plant processes and is often written as $\int L(x(t), u(t), p(t))dt$. In the previous example, $L()$ would cumulate all the costs of growing the lettuces related to the controllable inputs $u(t)$. For greenhouse tomatoes, where no final state is required because tomatoes are produced continuously, the function $L()$ would accumulate both the costs of controls $u(t)$ and the gains obtained from the crop represented by its states $x(t)$. The optimal control theory provides means to solve the problem of optimizing $J()$ with respect to $u$, under the constraint represented by $f()$. For a more thorough presentation of the optimal control theory, one can refer to Pontryagin et al. Bellman and Dreyfus and Lewis. Climate control application of crop models or crop processes models within the framework of optimal control also requires a model of the greenhouse climate because the control variables directly modify the climate. The plant behaviour is driven indirectly through its responses to the modifications of the environment.

In one of its simplest forms, the climate optimization problem is defined as: using a crop dry matter accumulation model and an algebraic expression of the greenhouse climate model, find the day- and night-time temperatures that maximize a cost function balancing the relative growth rate and the heating costs. CO₂ enrichment can also be included. Gal et al., Seginer, Seginer et al. and Critten showed that under the hypothesis that the dry matter evolution can be written as $\frac{dw}{dt} = s(w) \times f(u)$ the optimal solution can be expressed as a direct function of the external climate conditions for each time-
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instant independently. In practice this allows for the off-line computation of lookup tables that indicate what actions should be taken at current conditions. However, no real experiments have put these results to the test. Seginer et al. have studied the temperature optimization problem, only based on plant need. They used a dynamic model of the carbon balance of the crop (Fig. 10.5) with a temporary carbohydrate pool to derive the day and night temperatures that maximize the relative growth rate for a given daily radiative flux. The results are that young crops need higher temperatures than old ones where maintenance respiration is more important and that for a given situation, several couples of day and night temperatures are optimal (Fig. 10.6). Tchamitchian et al. and Tap et al. have used a dynamical greenhouse model instead of an algebraic one to introduce the damping of temperature due to the structures in the greenhouse. Solving the climate problem, either for tomato or for lettuce, respectively, proved to be a rather difficult numerical problem.

More complex crop models have also been used within the scope of the optimal control theory to determine optimal daily climate set-points under the constraints of long-term crop production optimization. The first attempt to mention is the work of Marsh and Albright who tried to determine by simulation the optimal temperature set-points for lettuce production using a crop growth model. Seginer and McClendon addressed the same problem but using
Pontryagin’s minimum principle to solve the very same problem and found similar results. Later, Seginer and Sher⁹⁹ used the TOMGRO model to solve the problem for tomatoes. It should be noticed that these approaches hardly used a greenhouse model at all: the goal is to define optimal set-points trajectory along the crop cycle, namely to optimize the blue-prints already available for these crops. Coupling a dynamical model of the greenhouse climate to a lettuce growth model, van Henten¹⁰⁰ used the singular perturbation approach¹⁰¹ to tackle the problem of models with different magnitudes of time constants. A new development in this area (Tap, pers. comm.) applies the same method to a simplified tomato crop model. Daily optimization of the climate (so-called fast processes) under the constraint of long-term optimisation of the crop production (so-called slow processes) can then be solved.

The lettuce case, being simpler to study than the tomato case, has often been used as a preliminary case study before addressing the more complex case of tomato where growth, development and harvest occur at the same time. One important remark to be made is that although many theoretical applications of models to climate control have been studied, none or very few have been put to the test in practice. The reasons might be first because control engineering groups lacking the greenhouse facilities have done these studies and second because optimal control produces time-varying set-points which cannot be implemented on commercial greenhouse climate computers.

Fig. 10.6 Optimal day and night temperatures for a tomato crop, as determined from the tomato carbon pool model (see Fig. 10.5). The simulation is for a crop of LAI = 3.5, submitted to constant day and night temperatures and to a constant level of photosynthetic photon flux density (PPFD) during the day. Daylight period is 14 hours. The hypothesis for this simulation is that the C-pool level must be the same at $t = 0$ and $t = 24$ hours.
10.3.4 Fertigation control

In both field and greenhouse production, there is an increasing pressure to improve the policies of irrigation and fertilization, that should both satisfy the plant demand for water and nutrients and avoid losses of nutrients in the environment. At present, empirical methods are used; they should be improved with mechanistic models in development.

The supply of water to the crop must fit its water requirements. In soilless culture, irrigation is usually calculated based on radiation measurements. Several relations have been established between the crop water uptake and the incident radiation for tomato as well as for other vegetable crops (formula reviewed by Jolliet\textsuperscript{28}). The VPD should also be taken into account when radiation and VPD are uncoupled, for example in changing climatic conditions and when using systems of climate control such as thermal screens or fog systems\textsuperscript{35}. The water demand also depends on a crop coefficient that increases with the leaf area development. In soil culture, the availability of water in the soil compartment must also be considered. It depends on the hydraulic properties of the soil and on the root development. In the field, the rain flux must enter in the water balance.

In greenhouses, computers are used to monitor radiation and to control the quantity of water that is provided to open systems (on soil or soilless), that is, the calculated evapotranspiration plus about 25% run-off to avoid salt concentration in the root substrate. In closed soilless systems, the water input must fit the crop demand to maintain the total volume of circulating nutrient solution. In the field, new decision support systems are designed to calculate the proper water supply. For example, the IRRIGERE software, designed for field tomato, estimates the daily evapotranspiration from climate and crop development and the soil water reserve from the soil characteristics and the root depth\textsuperscript{102}. Irrigation will not meet crop demand when water stress is needed to increase the dry matter content of fruits. In that case, the objective is to exhaust the water available in the root zone at fruit harvest. With these constraints, irrigation is proposed when the watering dose gets higher than a threshold value of 3 mm.

Few attempts have been made to build fertilization strategies using models of crop requirement, even in soilless culture. In this cultivation system, nutrients are usually supplied in excess together with water. Therefore there is no way to control the crop growth or product quality through the regulation of fertigation. Recently, Marcelis \textit{et al.}\textsuperscript{103} proposed the combination of models and sensors to optimize the nutrient supply in closed systems.

10.4 Discussion of the methods and future trends

In the last decades, most of the modelling effort on tomato crop has been put on the carbon fluxes and development processes in relation to the crop environment. To a lesser extent, the plant–water relationship has received some attention. It should be noted that the results of these studies for the grower are far
from proportional to the invested time: practical applications to irrigation are more numerous and more successful than yield prediction or automated climate control systems.

Fruit quality, nitrogen runoff, and sustainable cropping techniques are nowadays the focus of tomato crop modelling, using the same physiological approaches that have been successful up to now. The expected results are explanatory models that could help to estimate crop nutrient demand or harvest quality. Although this trend will widen the number of processes that will be represented, model-based plant management will still suffer from the limited scope of available models, and from the time needed to obtain these models. For example, fruit quality is defined by several criteria (see Table 10.1), but only some of them are addressed in modelling studies. Other processes are hardly addressed, such as plant architecture which determines its ability to intercept light and which is also part of the grower’s perception of the state of the plant. Models on the effect of diseases or pest attacks are also largely unavailable, not to mention models predicting when and where the probability of physiological or pathological disorders is the highest.

To overcome these drawbacks, other modelling approaches can be successful. The SERRISTE project has opted to use artificial intelligence techniques to represent both the knowledge involved in the daily climate management task and in the crop’s response. Agronomical know-how, obtained from experts, is represented through a set of variables, which are constrained within a fuzzy domain and through a set of constraints relating these variables. For example, the target daily mean temperature domain is obtained by:

- computing an optimal temperature from the forecasted available radiation;
- making adjustments for the variety;
- positioning a 1°C window around this value according to the vigour status of the crop.

A constraint is expressed as a linear combination of variables, the result of being forced to belong to a fuzzy domain. As an example, the temperature difference between day and night (a linear combination) must belong to a domain extending from 2 to 5°C, values which may be changed depending on the current conditions (for example, switch from 5 to 3 if Botrytis has been observed). A constraint satisfaction algorithm determines the sets of variable values which satisfy all the constraints. Declarative knowledge and numerical models are mixed in what is called a knowledge base (see Chapter 5). Two years of experiments in extension services facilities in three different regions of France have proven the feasibility and the real agronomic success of this approach.

As proven by Guerrin et al., the combination of declarative and numerical models broadens the scope of the system that can be represented and thus may be a way to overcome the limitations of numerical models. Moreover, building a declarative model may on many occasions be faster and cheaper than the experimental and theoretical work that would be needed to obtain a numerical model of the same processes. However, design of hybrid models mixing
declarative and numerical knowledge and use of Artificial Intelligence techniques for crop management support is still limited.

10.5 References

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