HORTISIM: A MODEL FOR GREENHOUSE CROPS AND GREENHOUSE CLIMATE

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Abstract

A combined model for crop production and climate in greenhouses, HORTISIM, was developed. Existing models, developed by several research groups, of various aspects of crop growth and greenhouse climate have been integrated. HORTISIM contains 7 submodels (Weather, Greenhouse Climate, Soil, Crop, Greenhouse Manager, Soil Manager and Crop Manager) plus a simulation process manager (the "Engine"). Climate conditions inside the greenhouse can be calculated from outdoor weather. The use of energy, CO_2 and water can be quantified. Crop photosynthesis, dry matter production, dry matter partitioning and individual fruit growth in fruit vegetable crops can be simulated.
Validation of the energy balance of a Venlo-type glasshouse with a tomato crop in The Netherlands showed that difference between simulated and measured instantaneous air temperature was mostly less than 2°C (average deviation was 0.53°C).
Crop transpiration and dry matter production have been validated for Dutch and Israeli conditions. Daytime crop transpiration was simulated reasonably well, being overestimated on average by 8% for tomato in The Netherlands and 1% for sweet pepper in Israel. The Israeli results were quite sensitive to the choice of using mid-canopy or above-canopy temperature and VPD measurements as model input. In many situations simulated dry matter production agreed well with experimental data, although dry matter production of sweet pepper in Israeli greenhouses was overestimated by 28%. Dry matter partitioning in sweet pepper was simulated rather well when simulation was based on organ sink strengths, with dates of anthesis and harvest of non-aborted fruits as model input.

1. Introduction

Explanatory models are powerful tools to represent and combine knowledge in a generic way. Greenhouse production offers large potential for application of these models: the fact that the crop's environment is under close control, that often more than one crop is grown in a year, and that the production costs per unit of production are high, make it worthwhile to plan and to optimise the production system carefully (Challa, 1985). A number of descriptive and explanatory models for greenhouse climate and crop growth has been developed during the last 20 years (reviewed by Critten, 1993 and Marcelis, *et al.*, 1998). However, only few models (e.g. Rijsdijk and Houter, 1993; Van

Henten, 1994; Jones, *et al.*, 1995; Gary, *et al.*, 1998) simulate both greenhouse climate and crop growth.

In a joint Dutch-Israeli project existing models of various aspects of crop growth and greenhouse climate, developed by several research groups, have been integrated in a greenhouse/crop simulator: HORTISIM. This simulation model was designed such that it could be used for different crops and for a wide range of purposes of many different users. This model of the greenhouse/crop system aims at predicting the amount and timing of production and the use of energy, CO_2 and water, as related to crop characteristics, crop management, greenhouse characteristics and greenhouse climate control. Predictions should be possible under the wide range of climate conditions prevailing in a temperate climate (e.g. in The Netherlands) and in a Mediterranean climate (e.g. in Israel). The model should enable studies on, for instance, the effects of greenhouse design, equipment, strategies for climate control and crop manipulation on crop production and resource use. An important aspect is the modular structure to enable adaptation of the model to specific questions and application and to facilitate integration with other models dealing with e.g. pests and diseases, the soil, plant nutrition or farm economics.

In this paper, a brief description and validation of HORTISIM is presented. The model is described in detail by Gijzen (1998a). Software engineering and object-oriented programming techniques adopted in this project are described by Cohen and Gijzen (1998).

2. Model description

2.1. General

HORTISIM 1.0 (HORTIcultural SIMulator) is a dynamic and mechanistic model for crop growth and greenhouse climate. Most parts of HORTISIM have already been documented as models or submodels elsewhere (e.g. Gijzen, 1992; Dayan, *et al.*, 1993; Marcelis, 1994; Heuvelink, 1995b). HORTISIM is composed of seven submodels plus a simulation process manager (the "Engine"; Fig. 1). Submodels (Weather, Greenhouse climate, Soil, Crop, Greenhouse Manager, Soil Manager and Crop Manager) call Tasks at appropriate time-steps. Tasks call Processes and Processes call Subprocesses. Which Submodel, Task, Process or Subprocess will be active at a certain moment is controlled by the Engine. An important feature of HORTISIM is that its configuration can be modified such that different subsystems can be activated or switched off and replaced by e.g. forcing functions. Furthermore, several Tasks or Processes are represented by alternative descriptions, from which the user can choose. For each Submodel the main Tasks and Processes are mentioned.

2.2. The Weather Submodel

Astronomical variables: outputs such as day-length, sun declination and sun position.
Global radiation: The diffuse and direct fractions of the instantaneous outdoor radiation are calculated as a function of the atmospheric transmission, according to Spitters, *et al.* (1986) and Gijzen (1998b).
PAR: The fraction PAR of global radiation and the diffuse and direct fractions of total PAR are calculated according to Gijzen (1998b).
Air temperature: Outdoor instantaneous temperature can be calculated from daily maximum and minimum temperatures.
Wind speed: Outdoor instantaneous wind speed can be calculated from a daily average.
Air humidity: Instantaneous air humidity has to be input.
Sky temperature: Sky temperature has to be input.

2.3. The Greenhouse Climate Submodel

Greenhouse transmission: Shortwave radiation transmission is calculated for Venlo-type glasshouses according to Bot (1983), while for other type of greenhouses transmission coefficients for direct and diffuse radiation must be provided. Transmission of thermal screens can also be taken into account.
PAR and NIR: The direct and diffuse fluxes of PAR and NIR inside the greenhouse are calculated from the outdoor direct and diffuse fluxes and greenhouse transmission.
Air temperature: Air temperature is calculated from ventilation rate and convective heat fluxes from the crop, soil surface, greenhouse cover, heating system and possibly screen. Convective heat exchange coefficients are calculated according to De Zwart (1996).
Cover temperature: The temperature of the greenhouse cover is a function of absorbed short-wave radiation, thermal radiation, convective heat flux and condensation, according to De Zwart (1996).
CO_2 concentration: The CO_2 concentration of the greenhouse air is calculated as a function of ventilation, crop net CO_2 uptake, outdoor CO_2 concentration and CO_2 enrichment.
Air humidity: Humidity of the greenhouse air is calculated as a function of crop transpiration, ventilation, condensation on cover and/or thermal screen, and soil evaporation, with exchange coefficients at cover and screen calculated according to de Zwart (1996).
Ventilation: The ventilation rate of Venlo-type glasshouses is calculated as a function of wind speed, difference between outdoor and greenhouse temperature, window opening and number and size of windows, according to De Jong (1990).

2.4. The Soil Submodel

Temperature: The energy balance of different layers is calculated. Temperature of the top-layer depends on absorption of short-wave radiation, thermal radiation exchange, convective and latent heat exchange with greenhouse air and conductive heat exchange with the subsoil, according to de Zwart (1996). Temperatures of lower layers depend on conductive heat exchange with adjacent layers.
Water content: This is a function of evaporation, irrigation and water uptake by the crop.

2.5. The Crop Submodel

Radiation absorption: The profiles of PAR and NIR absorption within the canopy are obtained according to the SUCROS model (Spitters, 1986; Goudriaan and Van Laar, 1994).
Transpiration: Crop transpiration is calculated using the big-leaf approach. For both the sunlit and shaded part of the canopy the energy balance is calculated with the Penman-Monteith equation (Monteith, 1965). The leaf conductance is calculated by a Jarvis-type equation (Jarvis, 1976) with responses to absorbed PAR and air vapour pressure deficit.
Canopy temperature: Canopy temperature is calculated from absorption of short-wave radiation and thermal radiation, transpiration and air temperature.

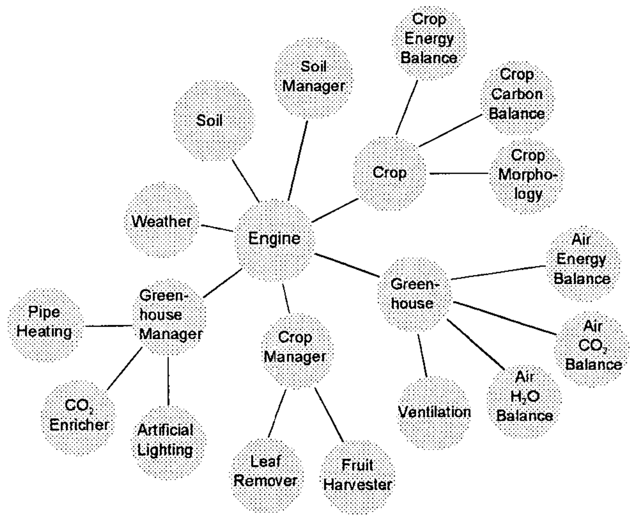

Figure 1: Schematic representation of Submodels, Tasks and the simulation process manager (the "Engine") in HORTISIM.

Dry matter production: Dry matter production is determined by gross photosynthesis and respiration.
Photosynthesis: Canopy gross photosynthesis can be calculated by (1) a simple analytical model of photosynthesis of a closed canopy described by Acock, *et al.* (1978), or (2) according to the SUCROS model (Spitters, 1986; Goudriaan and Van Laar, 1994), calculating leaf gross photosynthesis with the biochemical model of Farquhar, *et al.* (1980) at various depths in the canopy.
Respiration: Maintenance respiration is calculated as a function of temperature and weights of the different plant parts. Growth respiration is calculated as a function of growth rates of the different plant parts, assuming a constant growth rate during a 24 h period.
Partitioning: Dry matter partitioning among plant parts can be calculated by (1) descriptive allometry: ratios between growth of the plant parts are a function of day number or by (2) sink regulation: the fraction of assimilates partitioned into an organ is proportional to the ratio between its sink strength and that of all plant parts. This calculation allows the simulation of the growth of all individual leaves and fruits (Marcelis, 1994).
Morphology: the formation rates of branches, nodes, leaves, flowers and fruits are primarily a function of the temperature. Flower and fruit abortion is calculated as a function of the sink/source ratio, according to Marcelis (1994).
Leaf Area Index (LAI): Leaf area growth can be calculated either (1) from the dry matter partitioned to the leaves and Specific Leaf Area (SLA) of the leaf area increment, or (2) from expansion of separate leaf layers, which is a function of their age, temperature and minimum SLA (Gary, *et al.*, 1995).

2.6. The Greenhouse Manager Submodel

The operation of various devices (windows, heating pipes, etc.) can be forced, but it can also be controlled by a simple climate control system. The set-up of the latter is similar to the one described by de Zwart (1996).

Lamps: Use of artificial lighting is based on a pre-set time schedule and/or threshold outdoor radiation levels.
Heating: Heating of the greenhouse by pipes or forced convective heating is based on set-points for air temperature.
CO_2 enrichment: CO_2 enrichment is based on a set-point for CO_2 concentration.
Window opening: Window opening is based on set-points for maximum temperature and humidity of the air.
Screen aperture: Aperture of screens is based on outdoor temperature and/or time.

2.7. The Soil Manager Submodel

Irrigation of soil: a time table can be specified for the rate of water supply to the soil.

2.8. The Crop Manager Submodel

Removal of leaf dry matter and leaf area: time-tables can be specified for the leaf area removed or the amount of leaf dry weight removed.
Harvest of fruits: a time-table can be specified for the fruit dry weight harvested, or individual fruits can be harvested based on crop specific criteria like fruit development stage.

3. Experimental set-up

Greenhouse energy balance - A tomato crop (cv. Marathon; LAI≈2.5) was grown in rockwool in a 560 m^2 size Venlo-type glasshouse in The Netherlands; the soil was covered with a white plastic sheet. At 3 days in late spring measurements were done on weather conditions outside the greenhouse (including sky temperature), window aperture, and temperatures of cover, air, heating pipes and soil.

Crop transpiration - During 9 days in spring transpiration was measured (lysimeter) on tomato plants (cv. Turbo; LAI≈2) grown in rockwool in a Venlo-type glasshouse in The Netherlands (Marcelis, 1989). Daytime air vapour pressure deficit (VPD) inside the greenhouse varied between 0.2 and 1.5 kPa. Sweet pepper (cv. Marzurka) was grown in Israel in a volcanic tuff peat mixture in a polyethylene greenhouse at an average outdoor global radiation of 20 MJ m^{-2} d^{-1}. From April till November the greenhouse was shaded (30% light reduction). Transpiration was measured in spring (LAI≈4) using a heat balance system (Flow-2, Dynamax) applied around the stem of the plant; air VPD inside the greenhouse varied between 3 and 7 kPa.

Dry matter production - Validation experiments for tomato (cv. Counter) in The Netherlands have been described as Expt. 3, Expt. 8 and Expt. 12 in Heuvelink (1995a). Plants were grown in soil at an average outdoor global radiation level of 15, 14 and 3 MJ m^{-2} d^{-1}, respectively. For sweet pepper in Israel the same crop as for the validation of crop transpiration has been used.

Dry matter partitioning - Sweet pepper (cv. Mazurka) was grown in rockwool in a glasshouse in the Netherlands at an average outdoor global radiation of 11 MJ m^{-2} d^{-1}.

4. Results and discussion

4.1. Greenhouse energy balance

Input in the model were global radiation, sky temperature, wind speed, air humidity, window aperture, temperature of the soil at the depth of the system boundary (1.5 m), and greenhouse characteristics like number of windows, window size and soil properties. The difference between simulated and measured soil surface temperature was mostly less than 2°C, cover temperature was underestimated more than 4°C at high solar radiation levels (data not shown). The difference between simulated and measured air temperature was mostly less than 2°C, and the average deviation was 0.53°C (Fig. 2). Results showed some overestimation at daytime, and some underestimation at night-time.

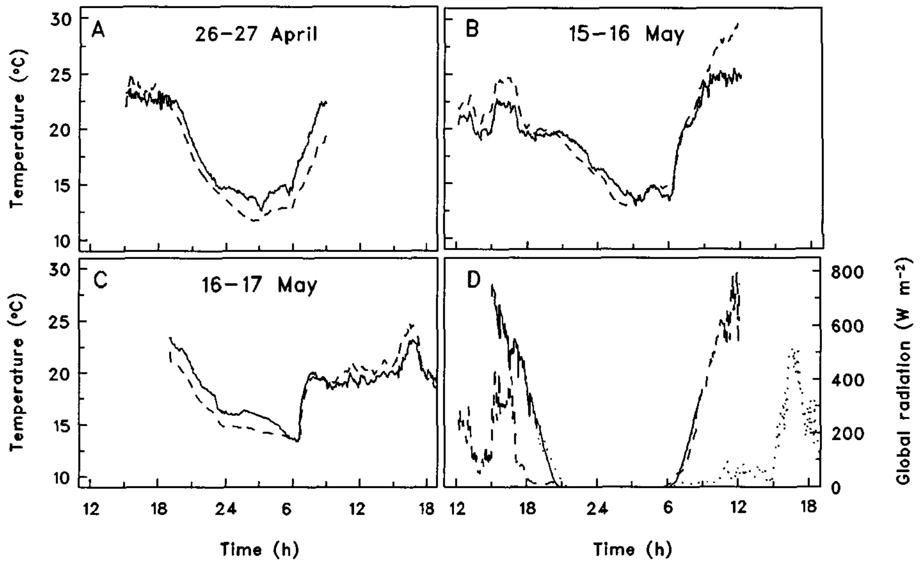

Figure 2: Measured (•, ——) and simulated (– – –) temperatures (A,B,C) in a Venlo-type glasshouse in The Netherlands. (D) Outside global radiation for 26-27 April (——), 15-16 May (– – –) and 16-17 May (⋯⋯).

4.2. Crop transpiration

Tomato in The Netherlands - Input to the model were LAI and 15 min. values of global radiation inside the greenhouse, air VPD, cover temperature and temperature of the heating pipes. Parameters of the stomatal response to absorbed PAR and to air VPD were taken from Bakker (1991). Daytime crop transpiration was simulated reasonably (Fig. 3A,B); averaged over 9 days overestimation was 8%.

Sweet pepper in Israel - Input to the model were LAI and 30 min. values of global radiation outside the greenhouse, sky temperature, greenhouse radiation transmission, air VPD and air temperature within the canopy and soil temperature. Leaf stomatal conductance was calculated as a function of absorbed PAR according to Fuchs' *et al.* (1995).

Crop transpiration was simulated adequately (Fig. 3C,D), when indoor air speed was assumed to be 0.1 m s^{-1}. However, actual air speed may have been higher, considering the frequent ventilation by fans and opening of a side wall. Averaged over 9 days, daytime crop transpiration was overestimated by 1%. Fast changes in measured transpiration were not simulated (Fig. 3C), since input of climatic data were 30 min. averages. For Israeli conditions it was found to be important whether input data for air temperature and air VPD were derived from measurements above or within the canopy. Using measurements above the canopy may result in a 50% higher simulated crop transpiration on days with very high air temperature and VPD (data not shown). The incorporation of a VPD-effect on stomatal conductance would probably have significantly lowered the simulated crop transpiration on these days.

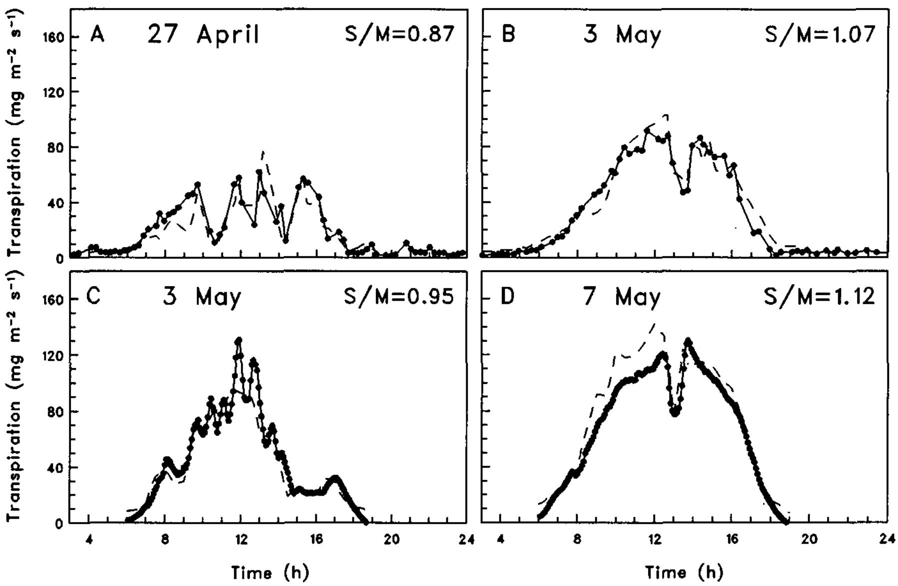

Figure 3: Measured (•, ——) and simulated (– – –) crop transpiration for tomato in The Netherlands (A,B) and sweet pepper in Israel (C,D). S/M is the ratio between simulated and measured daytime crop transpiration.

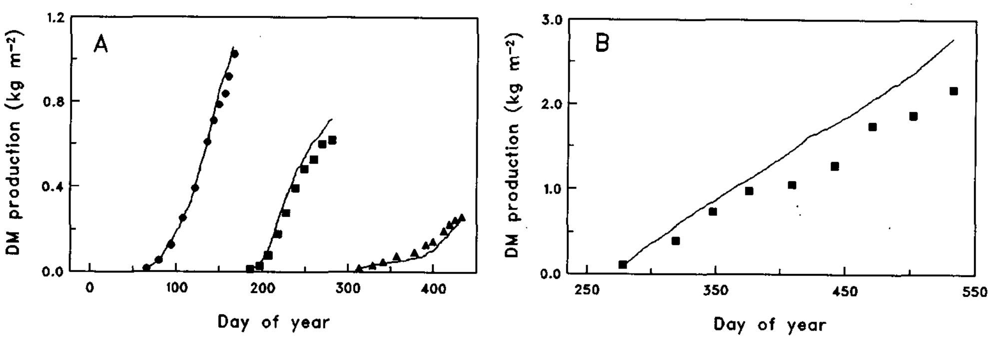

Figure 4: Measured (symbols) and simulated (lines) dry matter production for tomato in The Netherlands (A) and sweet pepper in Israel (B).

4.3. Dry matter production

Hourly averages for outdoor global radiation, greenhouse air temperature and greenhouse air CO_2 concentration, together with measured leaf area index and dry matter distribution were input to the model.

Tomato in The Netherlands - Dry matter production was simulated well, except for the winter crop, whose growth rate was under-estimated (Fig. 4A). This was observed before by Heuvelink (1995b), and probably results from an over-estimation of maintenance respiration at low irradiance, as HORTISIM does not take into account the influence of metabolic activity on maintenance respiration (Amthor, 1989).

Sweet pepper in Israel - Dry matter production was overestimated significantly (Fig. 4B), which may indicate that certain model parameters (e.g. photosynthetic characteristics) were not reflecting an Israeli sweet pepper crop. Another reason may be that actual Israeli cultivation conditions did not result in potential growth rates. This is also indicated by the crop light use efficiencies, being about 0.60 (g measured crop dry matter per mol PAR absorbed by the crop) in Israel, and about 0.75 in Dutch experiments (data not shown). Under Dutch conditions simulated and measured dry matter production for sweet pepper agreed quite well (Marcelis, Dogliotti and Heuvelink, unpublished data).

4.4. Dry matter partitioning

Predicted sweet pepper harvest (The Netherlands), with greenhouse climatic data, leaf area index and dates of anthesis and harvest of non-aborted fruits being input to the model, agreed well with measured harvest (Fig. 5). This means that partitioning was predicted well, as fluctuations in weekly harvest resulted from fluctuations in partitioning and not from fluctuations in dry matter production (Fig. 5). Although HORTISIM can simulate fruit set (or fruit abortion), this is a weak feature of the model, as for most crop growth models (Marcelis, *et al.*, 1998).

5. Conclusion

In many situations, HORTISIM predictions for both greenhouse climate and crop growth, transpiration and yield agreed well with observations. Unique is the structure of HORTISIM, which allows for a range of model configurations. It is a generic (not crop specific) model, though certain details are available for a few crops only. HORTISIM enables researchers to give a precise description of the model, its configuration and parameterisation and as such offers scientists the opportunity to repeat and analyse simulation experiments described in literature.

HORTISIM combines a crop model, a greenhouse climate model, a greenhouse climate management model and a crop management model. Hence, it can be used in studies on the effects of, for instance, greenhouse design, equipment, strategies for climate control and crop manipulation on crop production and resource use. The comprehensiveness and high configurability of the model has its drawbacks on the ease of operation, i.e. appropriately configuring the model for simulating an experiment.

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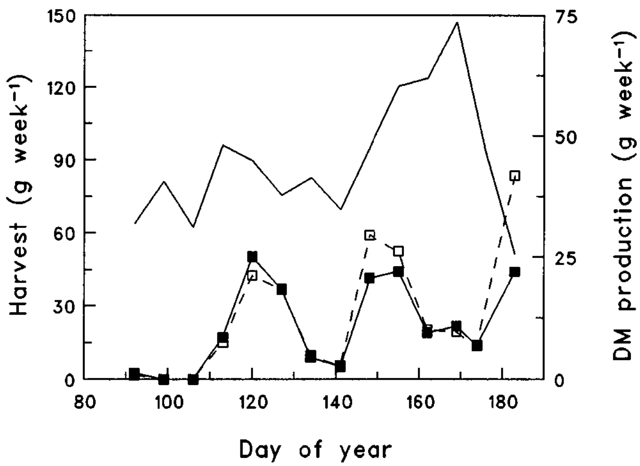

Figure 5: Measured (■) and simulated (□) weekly harvest of fruits and simulated dry matter production (——) of greenhouse-grown sweet pepper during a growing season in The Netherlands.

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