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Crop modeling and its use in vegetable cultivation

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Abstract : Agricultural models are mathematical equations that represent the reactions that occur within the plant and the interactions between the plant and its environment. Owing to the complexity of the system and the incomplete status of present knowledge, it becomes impossible to completely represent the system in mathematical terms and hence, agricultural models are images of the reality. Unlike in the fields of physics and engineering, universal models do not exist within the agricultural sector. Models are built for specific purposes and the level of complexity is accordingly adopted. Inevitably, different models are built for different subsystems and several models may be built to simulate a particular crop or a particular aspect of the production system.

Key words : Crop modeling, Vegetable cultivation

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Model is a word that admits several connotations, among which the following can be mentioned: (i) the representation of some entity, usually in smaller size than the original; (ii) a simple description of a system, used to explain it or to perform calculations (Crowther, 1995; Procter, 1995) (iii) an equation or a set of equations that represents the behavior of a system. It can be noticed, based on the above definitions, that models can be a prototype, a simplified representation, as well as an abstraction of a reality (system). To simulate means to imitate, to reproduce, to appear similar (Pereira, 1987). In agriculture, the simulation is important to forecast the results of a certain system management or of a certain environmental condition (Wu *et al.,* 1996).

Why to use crop simulation modles?:

Crop management challenges:

Agricultural producers, consultants, service providers, and industry representatives are faced with crop management and cropping system decisions throughout the growing season. The need of the agricultural person to manage and predict crop behavior over a wide range of planting dates, geographies and crops has become increasingly important as the need (value) for good, timely decisions and a decision making process has greatly increased. Use of crop simulation models incorporating local climatic conditions with management operations may increase the agricultural person's ability to make more timely and educated decisions.

From the lab to the field:

Scientific crop growth simulation models have traditionally been used to address research problems, answer questions and most importantly, to increase knowledge on crop growth, development and yield. The time has finally arrived in which crop modeling tools are increasingly being deployed in producer fields to help address questions and problems on a larger, farm scale size. The full potential and value of crop models have not yet been realized in production agriculture.

In season management decisions affecting yield :

The emphasis in production agriculture has been placed on attaining the maximum yield possible, or obtaining the most economical yield. What is often not well understood is that yield is determined during the growing season when critical crop management decisions are being made on a daily basis. Final crop yield is often dependent on the quality and timeliness of the management decisions. Tools that gather and display crop development progress can aid the agricultural person in making accurate and timely decisions and can greatly enhance production and profitability.

Modeling phenology and yield:

The ability of a crop simulation model to predict crop development is inherently more accurate than its ability to predict end grain yield. This is simply due to the fact that most plants can be effectively characterized for growth based on accumulated growing degree days, which is easy to measure and calculate and is less affected by other environmental influences. Furthermore, the accuracy of the model's output decreases as the season progresses due to the accumulation of errors through time. Crop yield is an accumulation of several predictions of physiological processes through time and inherently has the most errors associated with it.

Practical application of simulation in vegetable cultivation:

A scientifically interesting model contributes to our understanding of the real world because it helps to integrate the relevant processes of the system studied and to bridge areas and levels of knowledge. It helps also to test hypothesis, to generate alternative ones and to suggest experiments. Briefly, the scientific value of a model is its contribution to the development of science. A good predictive model simulates accurately the behavior of a part of the real world in situations where its behavior has been, or has not yet been, observed. It is, therefore, a good instrument to apply scientific knowledge in practice. It should predict reasonably well over a range of boundary conditions, to provide its users with alternative solutions of a problem. Several simulation models have been developed and used effectively in different fields of vegetable cultivation.

Use in protected farming:

Short *et al.* (1998) reported that a decision model for hydroponic tomato production (HYTODMOD) was developed for achieving high yields and high quality fruits. The model was based on 5 key tests during each of 5 growth stages (germination and early growth, seedling, vegetative, early fruiting, and mature fruiting). The 5 key tests included hydrogen ion concentration of the feeding solution, electrical conductivity of the feeding solution, root temperature, greenhouse air temperature, and air relative humidity. Optimum ranges for the 5 tests were developed HYTODMOD and utility theory was used to prioritize actions needed to correct unacceptable test levels. Thirteen growth response functions (GRFs) were necessary to represent the potential influence of key test variables on the growth of the tomato plant throughout the entire production period. HYTODMOD was validated by comparing the model recommendations with 4 experts who were each given 25 hypothetical and random production situations.

In the single-truss tomato production system (STTPS), plants are grown hydroponically in a greenhouse with a single cluster of fruit per plant. One major advantage of STTPS is the ability to achieve uniform fruit quality on a planned schedule with predictable yield. To achieve high levels of greenhouse space utilization and a consistent harvest, several generations of plants are grown simultaneously with the plants being spaced periodically to maintain maximum plant canopy cover of the growing area, thereby maximizing utilization of space and supplemental lighting. As the production period depends on the amount of light received by the crop, it is essential to control the amount of supplemental light so that harvest dates can be predicted. Chiu *et al.* (1997) reported that simulation of the cropping cycle was programmed in visual basic to provide a management tool for the scheduling of lighting and the design of the lighting system. This programme is based on a previously determined relationship between light received by the crop between germination and first flower development and the time to harvest. It accepts location specific solar radiation data as a variable input and has been used to optimize scheduling for the New Brunswick, New Jersey, USA location.

Recent studies have shown that, for greenhouse tomato crops, high levels of humidity and low levels of light depress transpiration and lead to yield losses. These adverse effects could be avoided by properly controlling the greenhouse climate. This work provides the basis for an effective control, by measuring the effect of climate (air speed, vapour pressure deficit, solar radiation and CO_2) on tomato transpiration and by assessing 5 transpiration models (Jolliet and Bailey, 1992). The results depicted that transpiration rate increases linearly with solar radiation, air vapour pressure deficit and air speed; air temp., CO_2 concn. and pipe temp. have no significant influence. Five transpiration models were checked against measurements. A simplified Penman model gave good predictions on av. (-2%), but with strong individual variations. Stanghellini's and Jolliet's models were the most accurate (+3% and -8% on av. resp.) and predicted both solar radiation and dehumidification effects well because they take into account the effect of vapour pressure deficit on stomatal conductance. In contrast, air temp. and CO_2 influences on stomatal conductance are not significant and do not need to be included in a tomato transpiration model.

Natural ventilation and leakage rates were measured in a multispan glasshouse with a mature tomato crop as reported by Fernandez and Bailey (1992). The ventilation-rate measurements were made with 4 settings of the leeward ventilators (10, 20, 30 and 40% of the max. opening). The influences of wind speed, wind direction and inside-outside temp. difference were analyzed. The leakage and ventilation rate measurements were made with the dynamic tracer-gas method using N_2O (nitrous oxide). Wind speed was found to have a strong influence on both leakage and ventilation rates. No influence was observed from either wind direction or temp. difference, but the experiments were carried out in a windy area, where it was difficult to determine the influence of the latter parameter. A formula to predict the air exchange as a function of wind speed was obtained for each ventilator position. Another formula was derived for the ventilation flux per unit ventilator area and average wind speed as a function of the opening angle. Ventilation rates were predicted using an energy balance model of the greenhouse. Good agreement was obtained between values predicted by the energy balance model and the measured values for larger ventilator openings, but at low ventilation rates the agreement was poor. The results obtained were compared with those obtained using models developed by other authors. This enabled the influence of side-wall permeability on ventilation rate to be established.

Bailey (1991) used a simulation model with meteorological data recorded at ICARDA (Aleppo, Syria) to predict the temperature and vapour pressure deficits obtained in greenhouses with fan and pad cooling. The temperature of the air entering the greenhouse from the cooling pad depends on the external dry and wet bulb temp. and on the efficiency of the pad. Inside the greenhouse the gradient in temp. between the cooling pad and the air extract fans is influenced by the extent of crop cover, the amount of external shading and the type of greenhouse cladding. Compared with an unshaded, single plastic film clad greenhouse with no crop, the temp. gradient was reduced by 50 per cent when full crop cover was present, a further 45 per cent reduction was obtained with 50% external shading, and using double cladding provided an additional reduction of 20 per cent. The results showed that in a partially cropped greenhouse the plants should be positioned near the cooling pad. Shading was shown to be very effective in reducing the cooling requirement but it also reduced the photosynthetically active radiation. The value of a double cover increased as the ventilation was lowered, as it reduced the conductive transfer of heat into the house.

To determine the feasibility of CO_2 supply equipment in greenhouse culture, a simulation programme was developed by Houter (1990) that calculates the hourly CO_2, heat demand and daily crop production on the basis of hourly data of the outside climate.

Bailey and Richardson (1990) used optimization techniques to establish the highest financial return for a multispan film plastic covered greenhouse. The parameter varied in the optimization process was the angle of inclination of a symmetric pitched roof. The influence of this angle on the total natural light transmitted into the greenhouse over a season was calculated using a validated prediction model. This was converted to tomato yield assuming yield is proportional to the light integral, and then to crop value. The influence of roof angle on heat loss and the cost of heating was established using simulation models. Finally the influence of roof angle on the material required to build a greenhouse to meet the wind loads required by the national greenhouse building code was determined. The roof angle which gave the biggest margin between crop value and heating cost was modified by the cost of materials to provide the roof angle for which the greenhouse gave the highest net income over its life.

Harvest planning for heated greenhouse tomatoes is necessary in areas of labour shortage. A bio-economic model was developed by Biemond and Trap (1989) to estimate the expected labour requirements, incorporating factors such as plant status, greenhouse characteristics, outside and inside climate (temp., CO_2 conc. and radiation intensity). The model also estimates production and can be used as a base for optimizing CO_2 conc. and temp.

A dynamic simulator to predict the diurnal courses and vertical profiles of the microclimatic variables within a greenhouse cucumber row crop was used by Yang *et al.* (1990). A set of climatic variables as defined above the canopy were supplied as driving functions and/or boundary conditions. The simulated results were then compared with experimental data taken simultaneously with the input variables. Quantitative agreements between model predictions and measurements for each output variable were represented by a group of 11 statistical parameters. The index of agreement for the 5 major microclimatic variables - solar radiation, transpiration, leaf temp., air temp., and RH - varied from 0.92 to 0.99, indicating that the newly developed model of this study possessed a high predictive value.

Jones *et al.* (1990) reported that two separately developed simulation models were linked and used to evaluate different environmental control strategies in Florida, USA, tomato production greenhouses. POLY-2 is a model of double polythene, quonset-style greenhouse typical in Florida. It is a dynamic model that realistically simulates environmental control equipment actions. TOMGRO is a dynamic crop model that simulates (1) growth, (2) development, and (3) quantity and timing of yield of tomatoes. Both models are based on independent empirical data sets used for calibration and validation, respectively. The two models were linked by incorporating POLY-2 into TOMGRO as a subroutine. Historical weather data for Tallahassee, Florida and Raleigh, North Carolina, USA, are used by the POLY-2 subroutine to simulate greenhouse environmental conditions which are used in turn by TOMGRO to simulate development and growth of the tomato crop. During simulation runs POLY-2 keeps track of heating fuel requirements and TOMGRO keeps track of tomato yield. Simulations over a range of setpoints showed that the optimal setpoint depends directly on the price of fuel, the value of the tomatoes, and location.

Marcelis *et al.* (1998) reported that a mechanistic model KOSI was developed to predict the weekly fresh harvest weight of cucumber fruits and their quality. The model consists of modules for greenhouse climate, greenhouse light transmission, light interception by the crop, leaf and canopy photosynthesis, assimilate partitioning, dry matter production, fruit growth, fruit dry matter content and fruit yield. The minimum data needed by KOSI for harvest prediction are date of planting of the crop and date scheduled for the last harvest. When only this minimum data set is used, calculations are based on long-term average data on weekly global radiation and temperature outside the greenhouse. Instead of using long-term average weather data, predicted or measured weather data can be provided as input. Model predictions can be improved by providing more input parameters, such as temperature set-point and CO_2 concentration of the greenhouse air, plant density, fruit pruning, frequency of fruit harvesting and transmissivity of the greenhouse. Model outputs are weekly yield of total fruit fresh weight, fruit number, fresh weight and age of individual fruits and the percentage of second-class fruits.

Use in pest control:

Collier *et al.* (1992 reported that adult emergence and egg-laying by *Psila rosae* were forecasted in 1991 using simulation models and weather data collected weekly from 8 weather stations in the UK. The data used were derived from the daily maximum and minimum air temperatures and from soil temperatures at a depth of 10 cm. Forecasts indicated that insect activity was earliest at Wellesbourne and Mepal (central and eastern England) and latest at Aughton (northwest England). Forecasts were validated using data from Wellesbourne field plots and from commercial carrot crops in eastern England. Forecast and observed insect activity were separated into generations and compared on a cumulative percentage basis, so that differences in times to 10 and 50per cent adult emergence and oviposition could be compared. Generally, forecasted activities of the flies were accurate to within one week of the observed activities. It was shown that a minimum of 50- 100 flies/generation must be caught to ensure accurate forecasting.

A model using weather data was developed by Collier *et al.* (1990) to forecast attacks by the anthomyiid *Delia radicum* on crucifers. The model simulates development of a field population of *D. radicum*, beginning with the overwintering stage (diapausing pupa) and following development through the 1st, 2nd and 3rd generations. The model is based on a series of rate equations describing the relationship between the rate of development of *D. radicum* and temperature. Soil temperatures are used in the simulation of the development of eggs, larvae and pupae and air temperatures for the adult stage, taking account of aestivation and the onset of diapause. It is concluded that the model can forecast activity of *D. radicum* in any region, using local weather data or standard measurements of air and soil temperatures.

Damage to sugarbeet plants from aphid feeding and simultaneous beet yellows closterovirus infection was studied experimentally and analysed with a simulation model (Groenendijk *et al.,* 1990). Plant dry weight, leaf area and photosynthesis were measured in sugarbeet plants infested with viruliferous *Aphis fabae* and in comparable healthy plants, and the rate of assimilate withdrawal by the aphids was estimated from collection of honeydew droplets. A plant growth simulation model was used to calculate the theoretical effect of the two growth reducing agents. Assimilate withdrawal and leaf malfunctioning decreased photosynthesis and increased light scattering and respiration in yellow virus-infected leaves. Simulation results demonstrated that the aphids absorb a significant proportion of the assimilates produced by the plants, up to 70 per cent. Assimilate withdrawal by the aphids and leaf malfunctioning quantitatively accounted for the observed reductions in sugarbeet growth.

Use in mechanized farming:

Three once-over mechanical harvesting systems for cucumbers grown in Michigan were compared using a discrete state simulation model (Haffar *et al.,* 1992). The model was constructed using parameters obtained in two separate sets of experiments that studied and determined plant fruit dynamics as a function of time and harvester parameters. The simulation used a computer algorithm called CUCHARV. Inputs to the model included crop maturity state, farm size, fruit pricing structure, and number and type of harvesters. A set of machine economic parameters was also input and used to determine the cost of owning and operating the harvesting system using a built-in cash flow subroutine. The model calculated daily net cash returns, based on the cash value per fruit size grade diminished by the cost of harvesting on that day. The output also included the daily av. per ha and daily total per farm of fruit number and fruit mass per grade and the av. and total daily cost of harvesting. The model included a field trafficability subroutine to determine the sequence of go/no-go days on a daily basis for three locations in Michigan and for three soil types. Simulated and actual cucumber yield were compared in two case studies in Michigan revealing a future promise of the model to aid as a decision tool for farmers and processors.

Jones *et al.* (1991) used a model of the road-vehicle-load system was developed to enable prediction of mechanical damage in loads of horticultural produce during transport. The elements of the system were the road profile, the tyres, suspension and chassis of the vehicle and the produce, packaging and cushioning which constitute the load. The model used a force-characteristic description of the vehicle and load elements to calculate the energy absorbed by the produce. The energy absorbed in turn was used to calculate physical damage to the produce. The model was simulated on an IBM compatible PC and a predictor-corrector numerical solution technique was adopted. A parametric study, in which bruise volumes were predicted for apples transported in bulk bins at different locations on a hypothetical truck, traversing bumps over a range of velocities, showed that the model results agreed with measured values. This approach to predicting damage during transport was shown to have considerable potential.

A mechanism for lifting a row of seedlings between two belts, capturing them between two strips of non-adhesive tape, and rolling them onto a reel was studied by Cundiff *et al.* (1991). Simulations were done to evaluate the influence of certain design parameters on the control of tape velocity relative to belt velocity. Tape velocity exceeded belt velocity by more than 5 per cent for a 0.1 m reel core radius, consequently a 0.2 m radius was used. The simulations predicted it would take 50 m of row to fill a 1-m diameter reel with tobacco plants, 60 m for tomato, and 105 m for cabbage. At a 1 km/h ground speed, the time required to fill the reel was 181, 214, and 377 s for tobacco, tomato, and cabbage, respectively. Controller sample and hold intervals greater than 2 s were unacceptable because they allowed tape velocity to exceed belt velocity by more than 5 per cent.

Use in vegetable production:

Crop Syst VB – Simpotato, a crop simulation model for potato-based cropping systems (Alva *et al.,* 2010). These crop simulation models, coupled with field data, can predict the fate and transport of N while providing basis for improved crop management practices. The potato crop simulation model Simpotato was integrated into the multi-year, multi-crop simulation model CropSystVB to improve overall model capabilities for the assessment of N dynamics in potato-based cropping systems. In the integrated model, CropSystVB simulates the soil-water-plant-atmosphere system for a crop rotation, as well as the water and nitrogen budgets. When the crop in the rotation is potato, simpotato simulates potato growth and development and plant C and N balances.

Visser and De Visser (1994) validated a dynamic simulation model for onion growth (ALCEPAS), using data on leaf area index, bulb and green leaf DM production, bulb formation and date when tops fell over from independent trials at 4 locations in the Netherlands. The model performance in terms of bulb DM production was good under environmental conditions close to the optimum, but poor under stress situations. The model overestimated leaf area index and green leaf DM content. Bulb formation was simulated satisfactorily, while the timing of 50 per cent fall-over was simulated too early at low plant densities.

The tomato crop model, TOMGRO, was modified by Gary *et al.* (1995) to enable the simulation of growth and development of individual organs. Assimilate partitioning was based on sink strength. Validation of the model was sought by assessing the relationship between sink strength and fruit position in the beefsteak cultivar Capello. Sink strength increased with truss number and was higher for proximal than for distal fruits. When these factors were introduced into the model, acceptable predictions of number and weight of fruits/truss were obtained. A user-friendly interface was developed enabling the user to set crop parameters and initial conditions before simulation starts, and to modify climate and source/sink number during simulation.

Models for 3 different phases of broccoli development, the juvenile phase (from transplanting to when the apex reaches 0.3 mm), the head induction (vernalization) phase, and the head growth phase, were fitted to the data for the duration of the development phases from 3 years (1992-94) of field experiments in Denmark with 3 cultivars (Caravel, Shogun and Emperor) and 4 plantings per year (April, May, June and July) at 2 densities (50 x 40 cm and 50 x 20 cm) was used by Grevsen *et al.* (2000). The daily rate of crop development from transplanting to the end of the juvenile phase was described by a simple temperature sum with no optimum temperature. The estimates for cultivar-dependent thermal time requirements were 80, 100 and 130 day-degrees for Emperor, Caravel and Shogun, respectively. The head induction phase (vernalization) was modelled by a piecewise linear temperature response function with base, optimum and maximum temperatures. The estimates for base, optimum and maximum temperatures were 2.9, 16.3 and 29.7°C, respectively. The models for the juvenile and head induction phases accounted for 58 per cent of the variation in the observed durations from transplanting to head initiation. The head diameter growth was described by a quadratic relationship between log head diameter and temperature sum from head initiation (0.6 mm). The best description was found with a base temperature of 0^0C and a maximum temperature of 17^0C.

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