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Survey of Greenhouse Models

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1. Introduction

A model is a form explaining a part of a system of the real world by means of structures simpler than in the original system. The system here means a closed environment in which many complicated relationships among components exist. By using a model, we can understand a part of the system more easily or less expensively.

A greenhouse model is a mathematically simplified representation of a real greenhouse system, a very complicated system including climate and crops in the greenhouse. The extent of simplification depends on the modeler's interest and purpose. For example, if we want to know how much heat is needed to keep the air temperature in a greenhouse at a certain level in a winter night, we may neglect the plants growing in it. However, if we are interested in yield from tomato plants in a greenhouse, we must include the plants in our greenhouse model.

As mentioned before, greenhouse models are mathematical; therefore, each component of the greenhouse system, such as light intensity, fruit weight, leaf temperature, and humidity, is expressed by numbers in the models. The models are usually in forms of computer programs because computers are the best tool for treating numbers.

This review attempts to introduce the structure and use of greenhouse models rather than to deeply analyze philosophies of modelers or to summarize the conclusions which modelers reached after their experiments with the models. Some models published in Japanese journals may not have been included here.

The library research was done on papers published before March 1983; therefore, works published after that date are not discussed in this review.

A Japanese translation of this article is available from the senior author upon request.

2. Classification of models

2.1 Classification

The greenhouse models have been sorted, for this review, into the following groups:

(a) Empirical models;
(b) Static or steady-state models of the greenhouse as a single-component system;
(c) Static, multiple-component models;
(d) Dynamic, multiple-component models;
(e) Any greenhouse models that include the CO_2 exchange rate of the crop.

Steady-state models have variables which do not change with time, and dynamic models have variables changing with time. In addition, most greenhouse models are deterministic and not stochastic; in other words, once the environmental conditions around the greenhouse are fixed, the environment in the greenhouse and growth of the crop will be uniquely determined. Stochastic models will output probabilities, much like precipitation forecasts.

2.2 Empirical models

The empirical or black-box models are based on observations with no consideration of physical principles. They are suitable for use in algorithms to control greenhouse climate by a computer (Bot et al., 1977; Udink ten Cate, 1980). The empirical approach has also been used to calculate the heating requirement of greenhouses (Schockert and Von Zabeltitz, 1980; Strom and Amsen, 1981; Bot, 1980). These empirical functions of heating requirement, which depends on the environment outside the greenhouses, are basically statistical

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quantifications of the experience of house managers and are specific to greenhouse type, region, and synoptic weather conditions. However, they are simple, easily understood, and sometimes quite accurate. Strom and Amsen (1981) gave a linear regression of heating fuel consumption vs. ambient air temperature, and the coefficients of the regressions ranged up to 0.95. Empirical models can be used as a part of a more complex model, such as the model of Krug and Liebig (1980), in which greenhouse climate is part of a climate-growth-economics model.

2.3 Static or steady-state models of the greenhouse as a single-component system

This kind of model is based on the energy balance of a greenhouse. A simple model of this kind considers the gain of heat by solar radiation and the loss of heat, given by the product of the temperature difference between the inside and the outside and an overall heat exchange coefficient, or U factor, to the environment. The sum of the two terms yields the heating or cooling requirement (Horiguchi, 1978; Lovseth, 1981; Tantau, 1980). Seginer (1980) and Seginer and Albright (1980) used a similar model in an economic optimization study.

The more complex models of this kind consider the various heat transfer processes separately. They usually state the energy balance for the interior air for the case of no ventilation, although some models used the energy balance of the roof instead (Garzoli and Blackwell, 1981). The most-often-cited reference for the major work of this kind is Walker (1965), who predicted air temperatures in ventilated greenhouses. Price and Peart (1973) used Walker's steady-state model, and they considered the soil heat storage, which Walker neglected, in a dynamic model of a power-plant/cooling-lake/greenhouse complex. Rotz et al. (1979) also used Walker's model to study the effect of three insulation materials — a cover, an inside curtain, and an insulated wall — and three collection techniques: a flat-plate collector with water storage; a flat plate collector with air as the working fluid, and rock storage; and an internal collector/storage device. Ewen et al. (1980) studied the energy balance of a greenhouse heated with air from a mine. Other models similar in nature to Walker's model are those of Von Elsner (1980), and a second analysis by Horiguchi (1978).

Using a single-component model, Morris et al. (1958) evaluated the effect of liquid films on greenhouse roofs. Garzoli and Blackwell (1973) emphasized the ventilation rate as a function of temperature differences in their simulation study. Landsberg et al. (1979) simulated a series of static points on 15-min intervals to describe a quasi steady-state diurnal pattern of air temperature. Uchijima et al. (1979) measured the components of the energy balance of a greenhouse and then solved the model for ventilation rate. Duncan et al. (1981) studied heating requirements and conservation potential with such a model.

2.4 Static, multiple-component models

Models in this group consider the energy balance of several components of the greenhouse separately; they are usually the interior air, the roof, the crop canopy, and the soil in the greenhouse. Typically, the components above the ground are considered as lumped parameters; namely, they are homogeneous with respect to state variables and descriptive parameters. The bulk soil is generally considered as a distributed parameter, which most often means that the soil is horizontally divided into several layers, each of which is considered a lumped parameter.

The initial work in this category was done by Businger (1963), who described many of the transfer processes for a steady-state model. Seginer and Levav (1971) did the second major work, including extensive review of the literature. They studied both physical laboratory models and computer simulation models, gave equations for a one-dimensional static model, and showed how the analysis could be extended to two or three dimensions. They also gave an analytical solution for the model under a sinusoidally varying radiation load. Selcuk (1981) solved the energy balance of a tunnel-type greenhouse in two dimensions and inserted it into a power/desalination/food-production complex for arid coastal regions. Selcuk and Tran (1975) modified Selcuk's (1971) model and accommodated a solar still in the greenhouse roof. The model by Iwakiri and Uchijima (1971) is similar to those described above.

Kimball (1973) described, in detail, a model that particularly emphasized the convective heat transfer coefficients. He included an extensive literature review, making it a very useful source of information. Maher and O'Flaherty (1973) studied the effects of evaporative cooling and polyethylene cladding using a model of this kind. Takami and Uchijima (1977a) described a steady-state greenhouse model and then used it in a larger dynamic model to evaluate enhanced soil heat storage (Takami and Uchijima, 1977b). Froelich et al.

(1979) presented an analytical solution to a model of this kind under periodically varying boundary conditions. Chandra and Albright (1980) studied heating requirements in greenhouses with night curtains. Amdursky (1980) described a partially finished model emphasizing short-wave radiant distribution. Kozai et al. (1978) also described a model under development with first emphasis on short-wave radiation and natural ventilation. They also developed the heat and mass balance of the model. Van de Braak (1981) developed a model to be solved with a hand calculator. Bailey (1981) described the exchange of thermal radiation in a greenhouse using electrical analogues and studied the effect of thermal screens. Kimball (1981) described an updated form of his earlier model designed to simulate a wide variety of greenhouse types.

The primary limitation of the static models listed above is that they cannot account for the storage of heat, or in other words, for the thermal history of the greenhouse. The complete energy balance equation for a component includes the product of the heat capacity of the component and the time derivative of its temperature. This term cannot be found in steady-state models because of the assumption that either the heat capacity or the time derivative is zero.

2.5 Dynamic, multiple-component models

The dynamic models include the heat storage term in at least some energy balances, while the steady state is assumed for the canopy. This is analogous to the two models mentioned earlier in which the greenhouse was considered to be a steady-state subsystem in a larger dynamic model (Price and Peart, 1973; Takami and Uchijima, 1977b).

Takakura made one of the earlier dynamic models to describe heat movement in a greenhouse at night. He extended the analysis to consider the effects of solar radiation by including heat generation equivalent to the absorbed solar radiation in the cover (Takakura, 1968). He later described a model (Takakura et al., 1971) that included the crop and air energy balances separatedly and that considered two-dimensional flux of heat in the soil. O'Flaherty et al. (1973), using an analog computer, analyzed the characteristics of temperature control of a heated greenhouse.

Von Elsner (1982) made a model to analyze the insulating materials of greenhouse. Written in SPECTRE, a simulation language, his model considered multi-layer crop canopy when the energy balance was computed. Bot et al. (1977), using the bondgraph, described a model programmed in a block-oriented simulation language.

Damagnez and Van Bavel (1978) reported a simulation model to describe the energetics of a greenhouse with a spectrally filtering fluid in the roof. Using the model, Van Bavel and Damagnez (1978) simulated conditions in both a fluid-roof and a conventional glass-roof greenhouse to find potential benefits of the fluid-roof concept and to determine how the system behaved in order to design elements. Sadler (1978) described tests of the model with some modifications for a plastic-roof greenhouse and used the model for a theoretical analysis of the significance of soil heat storage in the energy balance of a greenhouse. Van Bavel and Sadler (1979a) described an experimental greenhouse to verify the model for the fluid-roof and included data from the tests above (Sadler, 1978). A detailed user's guide of the model was prepared (Van Bavel and Sadler, 1979b). Damagnez et al. (1980) added a thermal link between the fluid storage tank and the ground water and studied the effects of the link.

Van Bavel et al. (1980) used several versions of the model to study crop conditions—temperature, water potential, and diffusive resistance of the leaf—in a ventilated glass house, in an evaporatively cooled glass house, in a fluid-roof greenhouse with a storage tank, and in a fluid-roof greenhouse with thermal connection to ground water. Van Bavel et al. (1981a) compared simulated conditions in a glass house and in a fluid-roof greenhouse for winter and summer weather in the southeast central Texas, U.S.A., and in southeast France. Van Bavel et al. (1981b) described tests of the fluid-roof greenhouse model and gave preliminary results. Heathman (1981) tested the ability of the model to predict crop water use in a greenhouse, and Shaer (1981) analyzed Heathman's data and suggested improvements in the model. Chiapale et al. (1983) tested the model with physical data taken from experiments in an improved design of the fluid-roof concept. The water/filter components were covered by a second sheet of clear glass.

Bot (1980) described the development of a model with emphasis on exchange of long-wave radiation and on natural ventilation. He was then attempting to develop submodels of water vapor and crop energy balance. Tantau (1980) described a model including the soil as a distributed parameter and treating the greenhouse as a first-order system with an imposed dead time. He applied the model to test strategies of microcomputer control. Short et al. (1980), using a model based on Walker's (1965) and Soribe and Curry's (1973) models, tested the effects of thermal screens and insulating pellets injected between two layers of the roof at night. Nir et al. (1981) studied the effectiveness of stratified soil heat storage using a one-dimensional numerical model. Cormary (1981) described briefly an apparently comprehensive thermal model developed by Electricite de France (EDF). His objective was to develop simple empirical models from his results to use in engineering control algorithms. Kindelan (1980) described a model in which only the soil had significant heat capacity. The temperature of the soil deep beneath the greenhouse was an output of his model rather than an input, which relieves the assumption that the temperature of the soil very deep beneath the greenhouse soil was the same as that outside. Straub (1980) reported a numerical model of the energetics of a combination of a greenhouse and a residence. His model was intended for use of residence designers who needed to know the effect of greenhouse plants on living space, especially with respect to interior humidity.

Glaub and Trezak (1981) described a dynamic analysis of the energy and mass balance of a tunnel-type greenhouse. Their model also simulated the solar radiation, normally an input boundary condition. Parker et al. (1981) extended the model of Soribe and Curry (1973) to include the simulation of pipes for warm water buried in the greenhouse soil. Chandra et al. (1981) described a model of the thermal environment of a greenhouse using the finite element method. In their model, the soil was considered in two dimensions with significant heat capacity, and components above the ground were considered in one dimension and at steady state.

2.6 Models including CO_2 exchange rate of the crop

The first model in this group was by Soribe and Curry (1973), who incorporated Curry and Chen's (1971) model of plant growth into a dynamic greenhouse model based on the model of Seginer and Levav (1971). In Soribe and Curry's model, the CO_2 balance of the whole greenhouse was not calculated; the interior CO_2 concentration was assumed to be constant. The link between the greenhouse and crop submodels was the leaf temperature.

Kozai et al. (1978) emphasized the short-wave radiation in their model and calculated photosynthesis as depending on photosynthetically active radiation and temperature, but neither the energy balance nor CO_2 balance of the greenhouse was calculated. The short-wave radiation penetrating into the greenhouse was calculated stochastically by Monte-Carlo techniques. Horie (1978) described a greenhouse crop model that included growth, respiration, leaf photosynthesis and temperature, partitioning of the photosynthate, and individual leaf expansion. The crop model was based on work by De Wit et al. (1970), and the greenhouse conditions were given rather than calculated. Inoue (1981) calculated the CO_2 balance in his model but did not include the energy balance of the greenhouse. Krug and Liebig (1980) included multiple-regression equations to predict crop growth rate and quality of the yield as a function of radiation, temperature, and time in their habitat, growth, and economic model. Van Bavel (1978) studied the advantages of the fluid-roof greenhouse over conventional design with regard to crop water use, humidity and temperature in the greenhouse, leaf potential, and the amount of CO_2 used in enrichment. Van Bavel et al. (1981a) simulated six temperature control methods for a CO_2-enriched greenhouse and a non-enriched control, for climatic conditions at Avignon, France.

Sadler (1983) introduced a crop canopy model by Takami and Van Bavel (1975) into Van Bavel and Sadler's (1979b) model and made an integrated greenhouse model with multi-layer canopy structure. He compared results from the two models with results from physical experiments.

3. Discussion

Although each model was built with different assumptions and for different purposes, the following three points can be compared: the environmental boundary conditions (inputs to the model), the components for which energy balances were kept, and the heat transfer mechanisms considered. In addition, major differences existed in the selection of coefficients of convective and diffusive heat and mass transfer, as well as whether they were constants or state-dependent variables.

Almost all detailed models had short-wave solar and long-wave sky radiation, air temperature and humidity, and wind speed as the environmental variables. Most of the modelers specified the soil temperature at some depth—although Kindelan's (1980) model computed the deep soil temperature affected by the greenhouse above. Those models considering the CO_2 balance of the greenhouse also included the ambient CO_2 concentration (Van Bavel et al., 1981a; Inoue, 1981).

In nearly all models, the energy balance was calculated for the greenhouse cover, the crop, the air, and the soil. The dynamic models considered first the heat capacity of the soil, then the roof, then the air, with the crop rarely considered to have significant heat capacity. The soil was usually modeled in layers to a depth of 1–2 m. Special-purpose models considered the energy balance of other components also, such as enhanced soil heat storage (Takami and Uchijima, 1977b; Ewen et al., 1980; Nir et al., 1981) and water heat storage (Van Bavel et al., 1981a; Rotz et al., 1979).

Energy transfer mechanisms usually used were short-wave and long-wave radiation, sensible heat and latent heat convection, and conduction. Short-wave radiation was considered in various manners: one-dimensional models with constant transmissivity of the cover, those with transmissivity as a function of time, those which considered wall effects, and detailed two-dimensional roof transmission models (e.g., Kozai et al., 1978). Long-wave radiation was usually assumed to be absorbed and then re-emitted by the roof. Researchers who studied materials transparent to long wave radiation included the corresponding calculations. Convection of sensible heat was generally included between the roof and the outside air, between the soil and the inside air, between the roof to the inside air, and between the crop and the air. Convection of latent heat was generally considered from the crop and the soil to the inside air. Most models included condensation on the inner surface of the roof, but some did not consider subsequent evaporation. The models of Kimball (1973, 1981) also considered condensation and evaporation from the outer surface of the roof. Nearly every detailed model, except some studies of nighttime heat loss, included the effect of forced ventilation. Most of the models also considered infiltration at a rate generally dependent on wind speed. Most dynamic models included conduction of heat into the soil. Some models considered the energy balances of the two roof surfaces separately and included conduction through the roof, while the simpler models considered the roof as an isothermal lumped parameter. The model of Van Bavel and his coworkers was the only example of an attempt to simulate the energy, water, and carbon-dioxide balance of a greenhouse, starting from environmental conditions and using physical principles.

4. Application of the models to greenhouse study in Japan

We will now discuss points to consider when one applies, for uses in Japan, the greenhouse models mainly developed in the U.S. and the European countries.

4.1 Differences in materials of greenhouse

In Japan, cover materials of greenhouse have a large variety, but large polyethylene houses are unusual; on the other hand, not many PVC houses are seen in the USA. These differences can be treated by changing constants in the model, such as transmittance of the roof of the greenhouse, without modifying the structure of the model.

4.2 Differences in size and structures of the greenhouse

One dimensional models assume that heat and mass move vertically but not horizontally. This assumption is adequate for a large greenhouse; however, it may not appropriate for small greenhouses like tunnel-type greenhouses in Japan.

There are few models developed in western countries considering the soil-air heat exchange, the water spraying insulation, or multilayer thermal screens found in Japan. These additional components change the environment in the greenhouse dramatically. Therefore, it is doubtful that the conventional models, especially the models not based on physical principles, will be applicable. Some models, such as Kozai (1983), have been reported dealing with the special greenhouses in Japan.

4.3 Differences in growing techniques

Balancing between the vegetative growth and the reproductive growth has been, in Japan, the most important technique in greenhouse cultivation. Therefore, the greenhouse climate is not necessarily controlled for the maximum growth (dry matter accumulation). Also, because of the use of growth regulators and the high cost of fuel, the greenhouses are managed at lower temperatures than those in the U.S. or in Europe. As a result, each crop usually takes longer to complete. Some of the readers must have experienced surprise with the short seed-to-harvest periods (2–3 months for tomato) published in overseas papers. These differences also need be considered in models with crop models included.

5. Conclusion

As relationships among people, greenhouses, and crops become complex, the significance of models will be greater. Originally, models were replacements of experiments which were impossible to carry out, e.g., a model of the solar system or of military operations. Greenhouse models or other agronomic models require validation to determine how well they represent reality. This requirement seems to work as a restraint on modelers, so that they are not carried away by theories. Nevertheless, it is beneficial for the future of agronomy that, through modeling, there can be cooperation between people in different areas—such as greenhouse architects, growers, computer programmers, and economists.

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