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On-Line Computer Control System for Greenhouses under High Radiation and Temperature Zones

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ON-LINE COMPUTER CONTROL SYSTEM FOR
GREENHOUSES UNDER HIGH RADIATION AND
TEMPERATURE ZONES

by

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BARD Project US-871-84

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TABLE OF CONTENTS

	Page
Abstract	1
Objectives	2
I. Introduction.	3
Description of the Problem.	3
Review of Previous Work	4
Approach and Report Organization.	7
II. A Dynamic Tomato Growth and Yield Model	11
Introduction.	11
Model Description	12
Materials and Methods	19
Results	20
Discussion.	23
III. Calibration and Validation of the Tomato Model.	43
Under Israeli Greenhouse Conditions	
Introduction.	43
Methods and Materials	44
Results and Discussion.	49
Discussion.	53
Conclusion.	55
IV. Optimal Growth Control of Greenhouse.	71
Tomato: Methodology and Some Results	
Abstract.	71
Notation.	72
Introduction.	74
Optimal Control and a Simplified Procedure.	75
Models.	78
Optimization.	81
Computational Shortcuts	83
Results	84
Sensitivity Analysis.	88
Discussion.	89
Conclusions	92
V. A Dynamic Model for Florida Greenhouses	103
Introduction.	103
Model Development	103
Model Calibration	116
Calibration Results and Discussion.	121
Validation.	130
Sensitivity Analysis of Model Parameters.	132
Discussion.	139

TABLE OF CONTENTS (continued)

	Page
VI. Economics of Temperature and CO ₂ Control.	142
Under Florida Conditions	
Introduction.	142
Methods and Materials	143
Results and Discussion.	153
VII. Supervisory Expert System Greenhouse Controller	161
Introduction.	161
Methodology	162
Supervisory Level Component	164
Conclusions	173
VIII. Testing a Supervisory Expert System	184
Controller in a Greenhouse	
Introduction.	184
Problem Statement	185
Methods and Materials	186
Results and Discussion.	192
Conclusion.	196
Implications for the Tomato Greenhouse.	196
Controller	
Description of Cooperation	199
Evaluation of Research Achievements.	200
List of Publications	203
Appendix	A-1

ABSTRACT

Greenhouse production of tomatoes and other crops has steadily increased in the southern US and in Israel where sunlight is abundant and temperatures are high. Greenhouse environment control strategies developed under more northerly climates where temperatures are colder and sunlight is lower may not be optimal for greenhouse production in these moderate winter climates. The overall goals of this research were to investigate the response of the tomato crop to temperature, CO₂ concentration and sunlight and to develop a computerized system for controlling the environment of tomato greenhouses under Florida and Israel climate conditions. A physiological model of tomato growth and yield (TOMGRO) was developed to respond to temperature, light, and CO₂. Experiments were conducted in six outdoor environmentally controlled growth chambers to characterize the effects of these climate variables and quantify model parameters. Experiments were conducted in commercial scale greenhouses in Israel to adapt and test the model on a production scale. The model required re-calibration, especially the photosynthesis rate equation, using data from one treatment in Israel. Comparison with independent data from other treatments in 1985 and another experiment in 1986 indicated that the model could be used to study various control strategies. In Israel, the model was linked with a physical model of the greenhouse environment to determine optimal heating and CO₂ enrichment strategies. New optimization techniques, developed in this study, indicated that CO₂ enrichment has the potential to be economically viable and that it is considerably more advantageous after fruit start to mature. In Florida, a dynamic greenhouse model was developed and linked with TOMGRO and used to study the economics of different temperature and CO₂ setpoints. It was found that setpoints should be changed during the day depending on outside conditions. A supervisory expert system control program was developed to combine expert rules with model results for determining the best setpoints to use. This software, operating in a remote computer, received data from the greenhouse real-time controller, determined new setpoints, and transferred them to the real-time controller. An example prototype system was successfully operated in Florida to control misting in a large greenhouse for over one month to demonstrate the capabilities and practicality of the system. It was concluded that expert systems coupled with models can provide reliable, practical decisions for intelligently and safely altering the control operations of a real-time controller in a greenhouse. Additional work is currently underway to fully develop and test a system for controlling the environment in a tomato greenhouse based on the results from this study.

OBJECTIVES OF THE RESEARCH PROJECT

The overall purpose of this study is to adapt, develop and test a computerized system for managing greenhouse environments that dynamically makes CO₂ injection, ventilation and nighttime heating control decisions to economically optimize the total system. Emphasis is on a tomato crop growing in greenhouses operating in climatic zones with high insolation rates and correspondingly high temperatures. The specific objectives of the research are as follows:

- a. To adapt and test a physical model of the relationship between external and internal greenhouse environments for high radiation and high temperature zones.
- b. To develop a simple season-long tomato crop model for environmental control based on simple physiological models, expert knowledge of the crop's seasonal temperature and humidity requirements and on management of pests, diseases, crop quality, crop timing, etc., for use in establishing seasonal control strategies.
- c. To experimentally determine photosynthetic response of tomato plants to CO₂ concentration, temperature and light during vegetative growth under high radiation and temperatures. This model will be used in determining optimal CO₂ levels at the temperature and humidity established by the environmental conditions and the season-long production requirements.
- d. To integrate the greenhouse, control subsystems and tomato models into a greenhouse climate control software package of long- and short-term control decisions based on expert knowledge and, specifically, for optimizing CO₂ injection and nighttime heating controls.
- e. To test and calibrate the software as a controller in commercial-scale greenhouses in full-scale operation.

Chapter I. Introduction

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DESCRIPTION OF THE PROBLEM

Controlled climate agriculture has been developed to extend both the time and spatial regions for agricultural production and to decrease the risk of losses and instability due to year-to-year climatic variability. Thus, technology and economic development has ameliorated to some extent the divergence between the natural environment production potential and demand from major world population centers. By growing crops at times and in locations in which supply is limited, greenhouse products have high value. Maintenance of desirable greenhouse environments requires an array of control subsystems for which both fixed and variable costs can be very high per unit of product. To economically optimize the management of a greenhouse system requires costs to be minimized and earnings to be maximized.

The development of computer technology promises new capabilities for greenhouse control. Computers can be adapted to monitor external and internal greenhouse environments, calculate the cost of control to different levels, determine optimal control conditions based on the crop and on the goals of the grower, and it can operate switches and other controllers for heating, cooling, CO₂ injection, and other devices to obtain desired conditions. With the advent of this new technology, the profitable expansion of controlled environment facilities into new areas may be possible. Since the most extensive and technically advanced greenhousing in the world is located in Northern Europe and Japan, most of the sophisticated greenhouse control software currently available and being developed is for use in these regions characterized by moderate climates. These software systems are specific to the control requirements and prevalent horticultural practices in low insolation, low temperature, winter/spring production systems. As a result, they cannot be directly applied to computer controls for greenhouses in subtropical areas characterized by relatively high insolation rates and both low and high temperatures, such as Florida or Israel. Control technology for these regions must be able to handle hot as well as cold conditions.

For effective management, growers need a tool that can project the cost of operating different greenhouse control subsystems to achieve a range of internal greenhouse conditions as affected by external climate. Furthermore, the management tool should be able to relate how various growth environments could be expected to affect potential yield based on crop growth and yield response surfaces or on expert knowledge. Control algorithms should be designed to accommodate the growers' aims and know-how, which are related to the assumed crop responses in a much more complicated way than that which can be described in a set of models and formulas. Logical decisions, as well as the "magic" farmers' knowledge, has to be integrated into the "scientific" control software package. With this information, controls would not have to be based on static setpoints or on individual control subsystems, instead a computer-directed greenhouse could orchestrate its control decisions depending on particular daily conditions, projected crop value, choice among overlapping control devices and postulated relationships that exist between current environment and the expected timing, quality, and quantity of yield.

There are many different crops currently being grown in greenhouses in both Israel and Florida (tomatoes, cut flowers, ornamentals and foliage) that could benefit from improved control technology. Flexible and dynamic controls are needed for implementing optimal seasonal strategies that might vary from simple survival at one time to maximizing production at another. Also, development of new greenhouse control technology (e.g., computer controls, CO₂ enrichment and solar-heated, groundwater-cooled greenhouses) may result in profitable production of crops that would otherwise be marginal or non-profitable. For example, such technology might make it profitable to produce tomatoes in North and Central Florida. Finally, Florida winters have been colder during the last ten years than before (Thompson *et al.*, 1983; Diaz, 1984), resulting in large losses in vegetable and citrus production. The citrus industry in Florida (and the mango industry in Israel) would benefit from a more stable supply of seedlings to replace trees killed during freezes such as the Florida freeze of December 25-26, 1983. This apparent climatic trend and the observation that citrus seedlings grow more rapidly and vigorously under elevated CO₂ conditions (Koch *et al.*, 1984) make stable, profitable production of citrus and mango seedlings in technologically advanced greenhouses look promising.

REVIEW OF PREVIOUS WORK

Greenhouse design depends on the interaction between a crop's environmental requirements and expected climatic conditions for a region. Physical models of greenhouse climates have been used to predict internal conditions from external conditions, greenhouse structure, and the design and operation of control subsystems (Bot, 1983; Huang and Kato, 1984; Meyer *et al.*, 1984; Willits *et al.*, 1980).

These physical models can be used to calculate the seasonal energy inputs required to maintain internal conditions to specified control levels. They can also be used to evaluate design alternatives and estimate the probability level with which the greenhouse controls can maintain desired conditions for different climates. Thus, for various greenhouse designs and control systems, the costs of maintaining desired conditions for a crop in a particular climate can be computed. These projected costs can be used as the basis of an economic analysis comparing the expected profits and risks associated with production of a particular crop.

For short-term control algorithms, greenhouse climate models have proved to be useful (Udink ten Cate, 1983; Kimball, 1973; Takahura et al., 1983; Kozai et al., 1978; Jones et al., 1984c). Udink ten Cate presented a systematic framework for greenhouse climate feedback/feedforward control (GCFC) that uses physical (and biological) modeling concepts. From a physical point of view the controlling algorithms have to be based on the response of climate conditions in the greenhouse, the influence of the climate conditions outside, and on the structure and facilities of the greenhouse (glazing materials, heating or cooling systems, thermal screens, etc.). From a horticultural point of view the control program must account for climate regimes as they influence the crop and fruit growth, fruit development and quality, pest control and the possibility of disease development. A variety of simulation models describing such processes as crop growth, disease control and insect population dynamics are now available (de Wit et al., 1978; Hashimoto et al., 1981; Matsui and Eguchi, 1978; Fransz, 1974; Rabbinge, 1976). In greenhouse tomato production, vegetative and reproductive growth is regulated by the net rate of dry matter accumulation. Under the hypothesis that the net carbon flow into the plant must be maximized to realize fullest production potential, tactical physiological controls can be outlined. On a daily basis, net carbon accumulation should be maximized. Carbon gain can be enhanced by using supplemental lighting, CO₂ enrichment, and by maintaining optimal temperatures. Unnecessary respiration losses (de Wit et al., 1978) can be avoided by adjusting nightly temperatures according to plant sugar levels (Challa, 1976). Respiration can also be reduced by pruning excess vegetative plant parts. The partitioning of dry matter or photosynthate between different parts of the plants can be manipulated to affect fruit quality and yield. Fruit production in general depends on competition between plants, between vegetative and reproductive parts on a plant and between individual fruit on a plant (de Wit, 1960).

In an effort to organize and prioritize the decision-making process, Udink ten Cate (1983) defined a hierarchical system of control consisting of three levels:

Level One. A very short period of time (of order minutes to hours). This level will continuously control the climate and soil conditions around the plant. Setpoint-driven feedback and feedforward control algorithms in the computer will open and close devices such as

ventilators, heat convectors, irrigation and fertilization valves and pumps.

Level Two. A short period of time (of order hours to days). This level dynamically establishes setpoints to maintain plant conditions for each particular day during a specific part of the season in order to obtain optimal dry matter accumulation rates, fruit production rates, conditions to minimize disease potential, etc.

Level Three. A long period of time (of order days to months). The expected quality and quantity of economic yield are determined by the conditions maintained within a greenhouse over a long period of time (weeks). During any particular season optimal condition sets vary. To lead the crop to its economical optimum requires a dynamic control strategy. Assumptions about the relationship between greenhouse conditions and optimal dry matter levels, flowering, fruit set, fruit quality and quantity must be inserted appropriately for each part of the season.

In discussing the three levels of control, Udink ten Cate (1983) suggested the use of existing knowledge and expertise for developing level three. There are no crop production models that include all the relationships necessary for seasonally optimizing environmental parameters because of complexities in pest management, fruit set, fruit development and ripening, and quality. Thus, no single currently available model can be used to establish optimal control levels during the season. Level three does, however, lend itself to the use of expert systems (Kinnucan, 1984) methodologies for establishing temporal requirements for temperature and humidity control. There is potential for using crop response models at level two to maximize daily photosynthetic rate by controlling CO_2 level in conjunction with maintaining temperature and humidity levels (or ranges) specified from level three. Various control devices and actions could be used to obtain desired temperature, CO_2 and humidity. The availability of a model to predict photosynthesis as a function of CO_2 level, temperature, and humidity and a physical model of greenhouse climate would allow software selection of the control actions for optimizing photosynthesis on a day-to-day basis while minimizing cost. Level one control software already exists in various systems. It seems practical now to adapt the systematic approach presented by Udink ten Cate for controlling greenhouse climate, but with restrictions on the generality of levels two and three. In particular, level three should be based on expert knowledge and dictate the seasonal time sequence of temperature and humidity control. Level two would select optimal CO_2 control levels and control actuators on a day-to-day basis and pass to level one the specific control setpoints or decision rules to be implemented. Level one should contain feedback measurements for control, and it should contain feedforward control algorithms based on physical and physiological models of a very short time scale (seconds to minutes).

In summary, a flexible conceptual framework for computer control of greenhouse climates has been developed with three hierarchical

control levels. Some economic, physiological, and physical models that contribute to these three levels have been identified and could be available for application (Jones *et al.*, 1984c; Saffell and Marshall, 1983; Cooper and Fuller, 1983). However, previous work suggests that limitations exist in the implementation of this computerized framework to commercial greenhouse control systems. Primarily, the limitations are in the inability of seasonal crop models to include all variables that affect the decisions on climate control conditions during the season. We conclude that this limitation can be overcome by computerizing expert knowledge of "optimal" crop environmental conditions to provide seasonal changes in control conditions that also reflect the goals of the producer. This expert systems approach, coupled with selected short-term physiological and physical models, can be developed and implemented with current technology and is highly promising.

APPROACH AND REPORT ORGANIZATION

The overall goal of this research was to develop computer control capabilities to dynamically make CO₂ enrichment, heating, and ventilation control decisions to economically optimize the operation of greenhouse environmental control equipment. The research was divided into four related efforts:

- 1)physiological tomato model
- 2)physical greenhouse environment model
- 3)optimization and simulation studies to study environment control strategies
- 4)integrated computer control system using expert system and model.

The philosophy of a 3-level control system described by Udink ten Cate (1983) was adapted. A seasonal level control problem (his level three) was defined to determine the optimal season-long strategy for environment control. Thus, a season-long tomato growth and yield model was required that responded to temperature, CO₂ and light. In previous research, one of the authors (E. Dayan) had worked with H. Challa and H. van Keulen on a season-long tomato simulation model. This earlier work provided a basis for the development of the model (TOMGRO) described in this report. The model (described in Chapter II) was written in FORTRAN, responds to instantaneous values of environmental variables, and simulates development and biomass growth over a long season (200+ days). A model listing is provided in the Appendix along with technical documentation and instructions on its operation.

Experiments were conducted in Gainesville, Florida (USA) to quantify parameters for the model, using six computer controlled, outdoor plant growth chambers (see Chapter II). Experiments were conducted in Israel to adapt and validate the model to full size greenhouse production conditions (Chapter III).

A dynamic greenhouse environment model was developed and tested in Florida (Chapter V). This model was designed to link with TOMGRO for simulation studies. The simulation studies allowed the testing of any proposed temperature and CO₂ control strategy by computing inside greenhouse conditions at any point in time, the energy and CO₂ use required for the control strategies, the costs of control, tomato growth and yield, and net profit over a specified season length. Chapter VI provides economic comparisons of various simulated tomato greenhouse environment control strategies.

In Chapter IV, the tomato model TOMGRO was coupled with an existing greenhouse model in Israel for optimization studies. Because of the complexity of the tomato model, new techniques were developed to obtain near-optimal strategies for greenhouse environment control over a season. Results from the optimization and simulation studies were to be used to develop the supervisory level (ten Cate's level two) controller.

The real-time controller (ten Cate's level one) operates in the greenhouse to collect current environmental data and use it as feedback to actuate control devices. A supervisory level controller was designed to operate in a remote computer and periodically (hourly or more frequent) communicate new control setpoints to the real-time controller based on greenhouse conditions passed back to the remote system (Chapter VII). This system combined expert system software and a knowledge base with results from the optimization problem to provide reliable and safe setpoints for controlling a tomato greenhouse environment. Preliminary tests of a supervisory level expert system was conducted for one month without failure in Florida (Chapter VIII).

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