Ferentinos, K. P., K. G. Arvanitis, H. J. Tantau, and N. Sigrimis. 2006. Section 5.8 Special Aspects of IT for Greenhouse Cultivation, pp. 294-312 of Chapter 5 Precision Agriculture, in CIGR Handbook of Agricultural Engineering Volume VI Information Technology. Edited by CIGR--The International Commission of Agricultural Engineering; Volume Editor, Axel Munack. St. Joseph, Michigan, USA: ASABE. Copyright American Society of Agricultural Engineers.

5.8 Special Aspects of IT for Greenhouse Cultivation

K. P. Ferentinos, K. G. Arvanitis,
H. J. Tantau, and N. Sigrimis

Abstract. *This section presents the recent and near-future uses of information technology (IT) for greenhouse cultivation. After some introduction on the basic physical mechanisms that govern greenhouse cultivation systems, two different approaches to greenhouse management and control are analyzed, the horizontal aspect and the vertical aspect. Then, low-level control, medium-level control and management, and high-level management is discussed. An additional section categorizes and presents some of the latest tools and complete products for greenhouse control and integrated management.*

Keywords. *Greenhouse cultivation, Information technology, Control, Integrated production management.*

5.8.1 Introduction

Advances in information technology (IT) during the last decades have been applied to greenhouse cultivation, meeting the need for uniform year-round plant production. Plant cultivation in a controlled environment, such as that of greenhouses, is a very complicated process with numerous parameters that can directly or indirectly affect productivity. For these parameters to be controlled, all physical phenomena of the greenhouse environment have to be analyzed to calculate energy and mass balances. Feedback control relies only on real-time measurements, but for optimal control and better management, complete models of the physical [1,2] and biological [3-7] systems are sought. Physical systems are well-defined and have long been elaborated while biological systems are more complex and uncertain. Efforts in biophysical modeling have only recently reached a practical utilization stage [8] and have a long way to go to become a mature coupling of bioscience and technology.

However, the societal requirements for environmental respect and the consumer demands for quality, under global pricing competition, adds new dimensions and constraints in optimal management of a viable business. The driving force of integrated production management provides both the reason and the means for advances in this field. Bio-models (models concerning insects, disease, production, etc.) and IT implementations will need to reach new levels of achievement to become reliable and to be considered as necessary inputs to the production process. Cultivation technologies (hydroponics, robotic harvesters, plant factories, etc.) become mature and less costly as they gain widespread acceptance and this drives the needs for a knowledge-rich IT as we move from the information age to a knowledge-driven society. Efforts have started based on modern communication technologies to provide the missing bridge from the expert teams or knowledge bases to the low-level controllers of the production side [10].

The understanding of transport mechanisms leads to the estimation of energy and mass balances of the greenhouse system, where three main transport mechanisms can be distinguished:

- *conduction,* which takes place through the construction and the cover and in a large degree through the soil (heat only);
- *convection,* which takes place between the greenhouse air and the internal surfaces, like heating pipes, cover, plants, soil surface, etc., and between the outside air and the outer surfaces of the greenhouse as well as the inside depending on infiltration or ventilation (heat and mass); and
- *radiation,* which includes the transport of energy between the surfaces of all components inside the greenhouse by electromagnetic waves (light and heat).

Several components determine the energy inflow and outflow. For the greenhouse cover and structural part, energy inflow and outflow are composed of solar radiation, radiation exchange with the sky and the interior of the greenhouse, exchange by convection between the structural parts and the inside and outside air, and finally latent heat produced by condensation of water vapor inside the greenhouse. In the greenhouse air, energy is exchanged by convection with the structural parts and cover, the

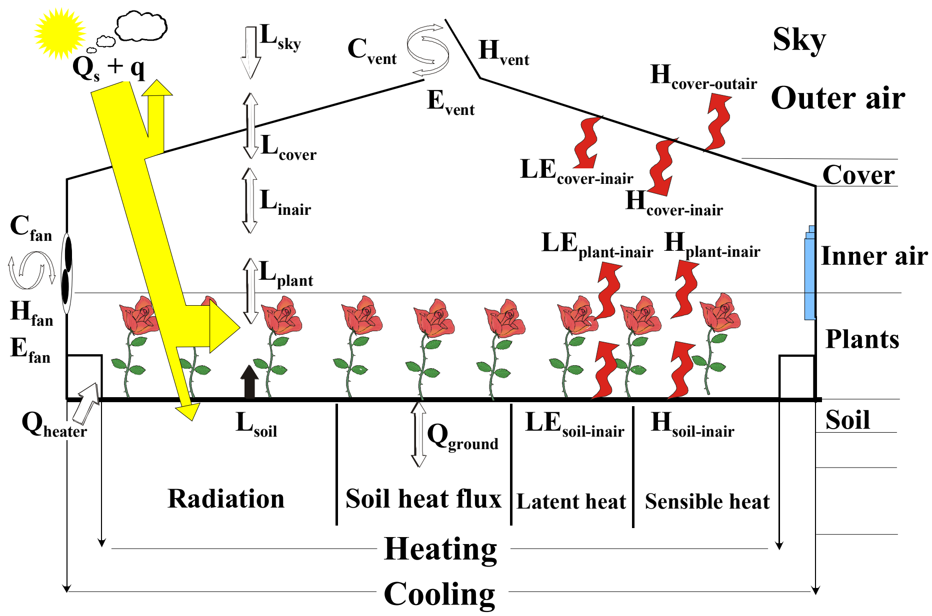

Figure 1. A schematic representation of physical processes of energy exchange in greenhouse crop production systems.

heating system, the soil and the plants, and of course with the outside air during ventilation. The soil exchanges energy by the absorption of solar radiation, radiation exchange with the greenhouse cover and its structural parts and the plants, convective exchange with the greenhouse air, and conductive exchange with the underlying soil layers. Finally, the plants absorb solar radiation; they exchange radiation with the cover and the structural parts of the greenhouse, the soil and the heating system; and they exchange energy by convection with the inside air and latent heat via evapotranspiration. The processes of thermal energy exchange among the greenhouse, the surroundings, and the greenhouse components are illustrated in Figure 1.

The thermal status of all greenhouse compartments is represented by the following differential equations:

$$Z_c C_c \frac{dT_c}{dt} = \left(Q_s a_c + q a_q\right) + \Delta L_{\mathrm{cover}} - H_{\mathrm{cover}-outair} - H_{\mathrm{cover}-inair} - LE_{\mathrm{cover}-inair} - LE_{\mathrm{cover}-outair} \tag{1a}$$

$$Z_i C_i \frac{dT_i}{dt} = \Delta L_{inair} + H_{\mathrm{cov}er-inair} + H_{plant-inair} + H_{soil-inair} - H_{vent} - H_{fan} + Q_{heater} \tag{1b}$$

$$Z_p C_p \frac{dT_p}{dt} =$$

$$(Q_s + q)\tau_c a_p + \Delta L_{plant} - H_{plant-inair} - LE_{plant-inair} \tag{1c}$$

$$Z_{s_o} C_{s_o} \frac{dT_{s_o}}{dt} =$$

$$(Q_s + q)\tau_c \tau_p a_s + \Delta L_{soil} - H_{soil-inair} - LE_{soil-inair} - Q_{ground} \tag{1d}$$

where T_c, T_i, T_p and T_{s_o} are temperatures of the cover, inner air, plant canopy and soil-surface, respectively. Z_x and C_x are the average height and thermal capacity of the compartment x. $H_{x\text{-}y}$ and $LE_{x\text{-}y}$ are the sensible heat and latent heat exchanges between compartment x and y. Because of the sign convention, $H_{y\text{-}x} = -H_{x\text{-}y}$ and $LE_{y\text{-}x} = -LE_{x\text{-}y}$. Q_{heater} is the thermal energy input from heating, and Q_{ground} is the ground heat flux density between the top soil and subsequent soil layers. a_x and τ_x are the absorption coefficient and transmittance coefficient of compartment x to the short wave radiation. a_c and a_q represent the absorption coefficient of glass to the direct and diffuse radiation respectively. For the soil compartment, only top soil temperature is described in Equation 1d. The soil heat flux density at the surface (Q_{ground}) is:

$$Q_{ground} = 2k_{so}\left(\frac{T_{so} - T_{s_1}}{Z_{so} + Z_{s_1}}\right) \tag{2}$$

which is determined by soil heat conductivity and temperature gradient at the top layer of soil.

The thermal status of other soil layers needs to be treated separately. Soil temperatures at various depths can be simulated with the following differential equation:

$$Z_{s_j} C_{s_j} \frac{dT_{s_j}}{dt} = 2k_{s_j}\left(\frac{T_{s_{j-1}} - T_{s_j}}{Z_{s_j} + Z_{s_{j-1}}} + \frac{T_{s_{j+1}} - T_{s_j}}{Z_{s_j} + Z_{s_{j+1}}}\right) \tag{3}$$

where j represents the jth sub-layer of soil

T_s = soil temperature

C_s= volumetric specific heat

k_s = thermal conductivity

Z_s = thickness of soil layer

The main measurable variables in a greenhouse environment are, for the aerial environment, temperature, relative humidity, light intensity, and carbon dioxide. For the root microenvironment they are pH, electrical conductivity (EC), soil temperature and moisture, salinity, and nutrient concentrations. The goal of greenhouse cultivation is the achievement of specific set-points for all these parameters, according to the appropriate desired values of the cultivated plants. This is carried out through some control and management operations in the greenhouse environment. These operations include, for the aerial environment, heating systems, ventilation and cooling systems, shading screens, supplemental lighting systems, and techniques for CO_2 enrichment. For the root microenvironment, according to the type of the cultivation system (soil cultivation or hydroponics), heaters, pH and EC control systems, and more general hydroponics management systems. Recently, more advanced decision-support systems that take the salinity tolerance of the cultivated plants into account have been developed [9].

All these systems and operations are bounded in complicated ways, thus the accurate control of the greenhouse environment is a challenging task that requires sophisticated methodologies. This is the so-called *vertical aspect* of greenhouse control and management (Figure 2), which makes the required control methodologies very demanding. The other major aspect of greenhouse control and management is the *horizontal aspect* (Figure 3), which refers to the different time scales of the involved processes in a greenhouse cultivation system [10,11].

Greenhouse cultivation systems consist of two quite different parts: the physical part and the biological part. The physical part is formed by the environmental parameters both inside and outside of the greenhouse, while the biological part is basically the cultivated plants, as well as any biochemical reactions taking place between the crop and the environment (such as soil or substrates, insects, diseases). The physical part has many effects on the biological part and at the same time the biological system has numerous influences on the enclosing environment. Generally, the physical systems of plant production respond quickly, while the biological systems respond relatively slowly [12]. This makes the control and management of the greenhouse environment even more difficult and complex.

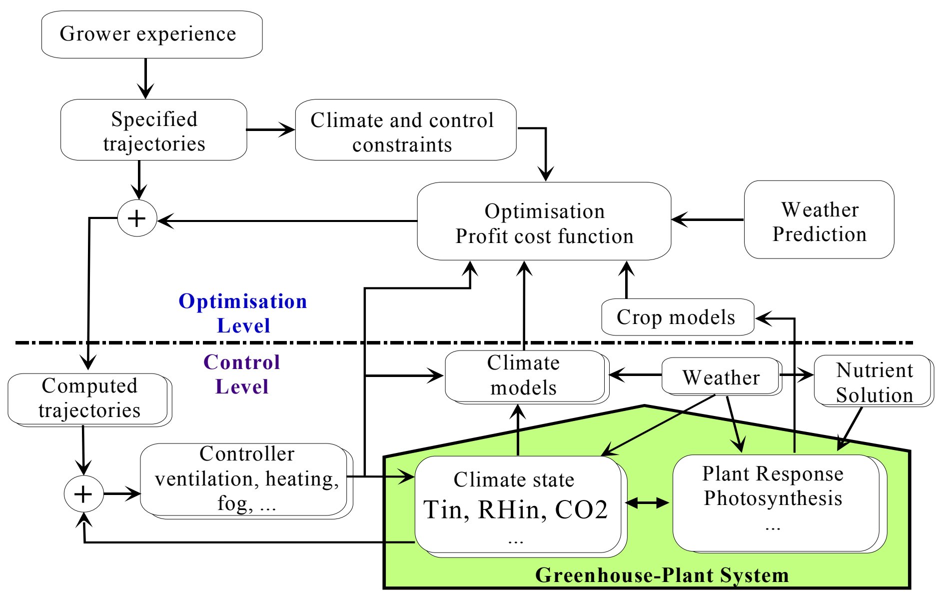

Figure 2. Vertical aspect of the greenhouse management and control problem.

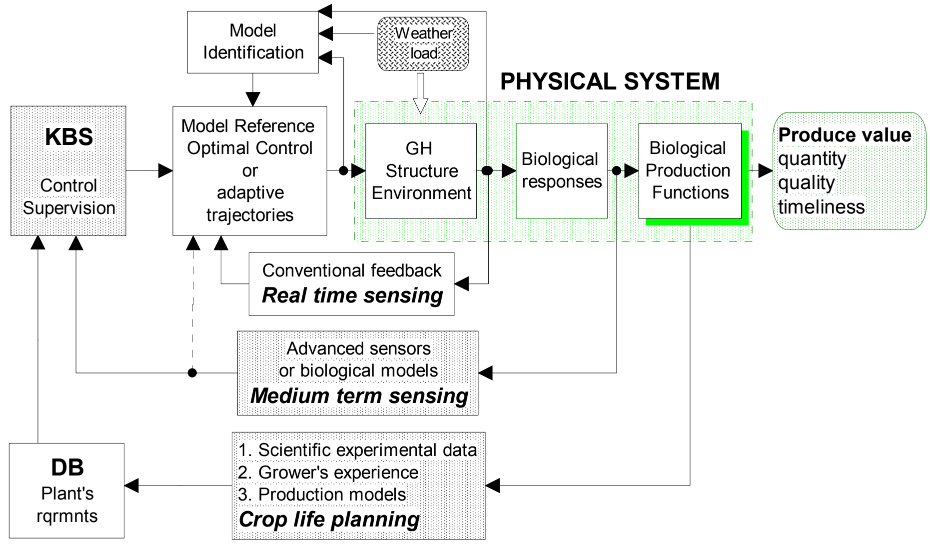

Figure 3. Multi-time-scale management and control of the greenhouse environment (horizontal aspect).

5.8.2 Low-Level Control Loops

The basis of greenhouse environment control consists of methods that use several aspects of IT to form low-level control loops [13-17]. They can be classified as classical control techniques or intelligent methodologies for real-time control.

Classical Control

In classical control, the systems to be controlled are considered as input-output systems. Inputs are usually control inputs and disturbances, while outputs are usually the variables to be controlled. In the greenhouse environment, control inputs can be the heating amount, the ventilation rate (window opening, speed of fans), the amount of supplemental lighting, the position of the shading screen, and the CO_2 enrichment rate. The outside temperature and humidity, the wind speed and direction, the solar radiation, and the outside CO_2 concentration are considered as disturbances. The outputs are the inside temperature, relative humidity, CO_2 concentration, and light intensity at plant level, i.e. the controlled variables.

The conventional control technique most widely used in greenhouse cultivation systems is feedback control. The controller is often of the simple ON/OFF type or the *proportional-integral-derivative (PID)* type. A PID controller has the ability to handle set-point changes, to compensate step-load disturbances, and to face wide model uncertainty [18]. To improve the management and control of a greenhouse process, an adaptive PID control strategy (Figure 4) may be applied to compute the optimal control signals used for a defined cost-performance function. Simpler versions of the PID controller have also been used in greenhouse environment control [13,19-21], which

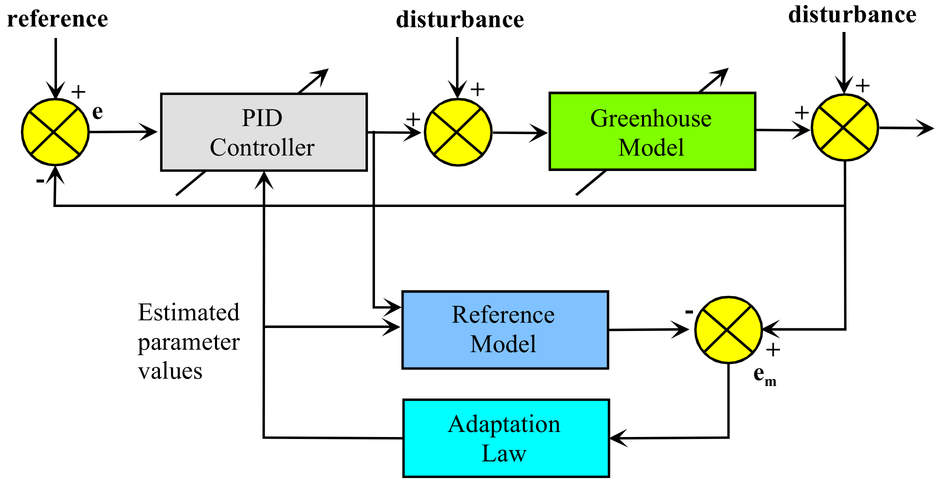

Figure 4. Structure of the adaptive PID controller.

has served greenhouse facilities for many years (at the start of feedback implementations) as switches (thermostats, hygrostats, pressostats). Because most greenhouse equipment is the binary-switch type, the application of such dynamic control methodologies is further complicated. In order for this type of equipment to be included in the dynamic control scheme, each of the dynamic equations for each possible state and control of the switching rate must be linearized, similar to pulse-width modulation [22]. A variation of the PID controller, the *pseudo-derivative feedback algorithm (PDF)* [23], has also been used successfully in temperature and humidity control of greenhouses [12,24]. Another control methodology, which originated by research in greenhouse environment control, is the *proportional-integral-plus (PIP)* controller [16], which has shown several advantages over the conventional PID or PI control, including robustness to pure-time transport delays, power and flexibility due to its state variable feedback, and a structure that avoids common control problems such as integral wind-up [25,26]. An improvement of the PID controller, the *Smith predictor* [27], compensates dead times that lower closed-loop stability margins and its performance. It has been used in greenhouse environment control with positive results [3]. Finally, an approach that leads to better temperature distribution and minimizes heat losses is that based on the nested control loop configuration and the load divider concept [28], which divides the input needs to the corresponding actuators, achieving better performance of the control system.

Intelligent Real-Time Control

Over the last few years, IT has been playing a growing role in the development and materialization of greenhouse cultivation control systems. In particular, methodologies of IT in the area of artificial intelligence (AI) have been widely used to develop highly sophisticated intelligent systems for real-time control and management of greenhouse facilities, where conventional mathematical control approaches do not easily apply [29]. Artificial *neural networks (NNs)* have been the most-used tool in intelligent control of both greenhouse environment and hydroponics. Their main advantage is that they do not require explicit evaluation of transfer coefficients or any model formulation. They are based on inherent learning capabilities of training data from the process to be modeled. Initially NNs were used in modeling the aerial environment of greenhouses, generally using as inputs the outside environmental parameters (temperature, humidity, solar radiation, wind velocity, etc.), the control variables, and the state variables, i.e., the conditions of the cultivated plants [30-32]. Simpler models that do not take into account the conditions of the plants have also been applied successfully in temperature modeling [33,34]. It should be noted here that NNs are usually bad extrapolators, meaning that they do not perform satisfactorily in conditions considerably different than those of the training data. In hydroponics systems, NNs have been used to model with great accuracy the pH and the electrical conductivity of the nutrient solution in deep-trough cultivation systems [35], as well as the photosynthetic rate of the cultivated plants [36]. Furthermore, NNs have been successfully used in control applications of the greenhouse environment [37]. Very recently, their combination with *genetic algorithms (GAs)* in hydroponics modeling has been proven even more successful than conventional neural network modeling [38].

GAs are another AI technique that has been applied to greenhouse cultivation management and control. Their ability to find optimal solutions in large and complex search spaces, together with their innovative design capabilities inspired by the simulation of natural evolution, make them very powerful tools for design and optimization in several engineering applications. They have been used as an optimization tool for controller tuning of the greenhouse environment [39], as training methodologies of neural network agricultural models [40], as optimizers that determine optimal set-point values [41-43], and as optimizers of other soft computing-based controllers like fuzzy controllers [44]. Another technique similar to GAs, the *photosynthetic algorithm* [45], is a biologically inspired optimization algorithm that simulates the optimization processes involved in photosynthesis by plants. It was successfully applied to the training of neural network agricultural models [40].

Fuzzy logic is a quite commonly used intelligent technique in advanced control and management of greenhouse cultivation systems. The complex processes and interactions of the greenhouse environment make the kind of soft control that fuzzy logic incorporates very powerful and successful in accurate control and management of greenhouse systems, either as fuzzy logic on its own [46,47], or in combination with GAs and NNs [41,44]. It has been used to provide superior scaling among different production system sizes and loads in ventilation control [48] and in staged heating and ventilating systems in greenhouses [49]. It has also been used to provide management decisions in intelligent real-time control of greenhouse environment and hydroponics [3,50].

5.8.3 Medium-Level Control and Management

The control schemes described so far can be used as the basic elements of medium-level control methodologies which form sophisticated systems for greenhouse management with two main focus areas: longer than instantaneous time-horizon control management and conflicting-resolving control management.

Medium Time-Scale Processes

As mentioned above, there are several different time scales in the processes involved in greenhouse cultivation. The first step in the development of sophisticated control schemes for medium-level control methodologies that deal with medium time-scale processes, with an aim for energy saving, involves the method of averaging some of the parameters of interest (e.g., temperature or light). This is possible because biological properties of plants indicate that they comprise integrating capacities, which means that short-term fluctuations of temperature or light intensity do not affect plants' growth as long as an average value of each parameter is maintained over a certain period [51-54]. Energy saving is achieved because, for example in the case of temperature integration, the developed technique requires a desired average temperature during some specific time period and not specific temperature set-points for specific moments. In this way, a methodology can be developed that adapts the low-level temperature set-point according to the outside temperature conditions, so that minimum heat losses are achieved, keeping in mind of course that some specific average temperature has to be achieved by the end of the integration period [55]. If a good algorithm can be found, considerable energy savings can be achieved.

Some early investigation on the development of such integrating control strategies, with a focus on temperature integration, was performed by de Koning, who developed an algorithm based temperature averaging for 24-hour periods [56], and later for periods of several days [57]. In [58] an algorithm is presented that compensates for periods of temperature deviations in a greenhouse by slowly modifying the heating set-point. The authors report good results in compensating for deviations either above or below blueprint temperatures. Timmons and Gates [59] developed a time-integrated approach to relative humidity control, and extended it to heat stress conditions for livestock [60] and optimal time-integrated variable set-points [61]. Marsh and Albright [62,63] presented a strategy for minimizing heating costs using an algorithm for calculating the economically optimum temperatures for greenhouse lettuce production. An alternative method based on formal optimization methods to achieve optimal set-points for greenhouse lettuce production was proposed in [64]. Recently, several more advanced control strategies that exploit the temperature integrating capability of plants to achieve considerable energy savings have been developed, using the technological developments of IT [65-68]. In the case of light integration, Albright et al. [69] developed a rule-based algorithm to maintain the accumulated light intensity to a consistent daily integral, while Ferentinos et al. [70] optimized that control policy in relation to the CO_2 concentration of the greenhouse environment, according to the rules developed in [54].

The integration control policy for some environmental parameter can influence and make problematic some other control parameters. For example, in the case of temperature integration, relative humidity can often fluctuate and reach dangerously high values [71]. In long-term control strategies, short-term dynamics of the plants should be taken into consideration [72]. Thus, integrated control of the greenhouse environment requires the development of greenhouse management systems with capabilities of conflict-resolving schemes [73].

Additional information that can refine and improve the control strategies applied in a greenhouse cultivation system can be provided by forecasts, which lead to predictive control schemes. Weather forecasts have been used to optimize control of temperature integrating strategies, with considerable energy savings [74], while, in other cases, neural network models have been used to simulate greenhouse behavior in response to anticipated meteorological conditions, so that the predictive control strategy materializes [75].

Hydroponics is the other part of a greenhouse cultivation system that includes medium time-scale processes and needs to be controlled and managed, together with the aerial environment. Irrigation scheduling and nutrient supply in hydroponic systems are crucial and require precise control to optimize quality and quantity of crop production and to minimize cost and pollution due to effluents. A design for a water supply controller using system identification was proposed in [76], but the proposed controller performs well only when a feedforward element is added in the control loop, in order to estimate water uptake as a function of global radiation. On the other hand, progress has been achieved in model prediction of crop irrigation needs. Usually, a transpiration model [77] that predicts plant transpiration based on ambient conditions of temperature, solar radiation, CO_2 concentration, and vapor saturation deficit is used, while hybrid approaches using simplified transpiration models to predict the necessary water supply have also been proposed [78].

Multi-Process Coupled Systems and Conflicts

Although biological systems consist of complex, inexactly defined, interacting processes, they have been until now treated with optimal control strategies that are applied separately to each process and not to the entire system as a whole [79,80]. The treatment of individual processes of a complex system, especially when those processes often conflict with each other (as in the case of greenhouse climate and hydroponics control), does not necessarily lead to the optimal solution of the entire system. The definition of set-points and constraints for the control of such systems is difficult and problematic. In addition, each process can contribute in a different and maybe changing degree to the final output of the system. Thus, conventional control methodologies encounter some major difficulties in situations where control variables are coupled; for example, temperature and humidity, which are highly coupled through nonlinear thermodynamic laws. In these cases, the control actuators are usually subject to changing characteristics, as the gain is largely perturbed by cross-product terms with disturbances. Another example of this kind of problem is addressed in hydroponics systems, where, when acid is added to the solution in order to reduce the pH value, then electrical conductivity is strongly affected. The same holds true during electrical conductivity control, in which case some fertilizers affect the pH value.

Recently, these kinds of control problems have been addressed for the case of temperature and humidity coupling [81] and the case of simultaneous temperature and CO_2 concentration control [82]. In [81], conflicts due to temperature-humidity coupling are faced through an approach that consists of a powerful combination of linearizing and non-interacting feedback/feed-forward controllers, outer-loop conventional dynamic controllers (e.g., PID or PDF controllers) as well as a pre-compensator and command generator module, which computes set-point trade-offs based on psychrometric properties and actuator limits and costs to provide optimized set-points that will allow the feedback/feed-forward controller to operate without hunting or chattering.

In a more general context, in cases of process coupling and conflicts each process can have its own local dynamic control system, optimally tuned to the local goal, which is defined in a general environment, taking into account the final output of the entire system. This context leads to the development of *multi-agent systems* that can lead to the resolution of conflicting control decisions in complicated situations during plant growth [83].

5.8.4 High-Level Management

Recent demands of product quality and production performance have made advanced crop management techniques and intelligent control systems absolutely necessary for the operation of modern greenhouse cultivation facilities. Traditionally, information systems have consisted of databases, application programs, and user interfaces. This practice is changing because the new demand is for open integrated architectures with a more global scope through cooperative action [84]. Knowledge-based information systems, database management systems, and intelligent control are increasingly being integrated into IT. Databases offer information sharing while new computational intelligence techniques allow data mining, multi-agent systems, planning, scheduling, and negotiation. Greenhouse cultivation management systems are becoming increasingly sophisticated and are using many of the advanced methods and tools of industrial automation, modern control theory, and IT. Computer and communications technologies are closely linked to these developments. All these make feasible the development of integrated management systems incorporating a high degree of intelligence and flexibility in the manipulation of long-term effects in the involved processes in the greenhouse cultivation system.

Long-Term Effects and Crop Lifetime Horizons

Several models have been developed to predict growth rate as a function of environmental parameters, with a final goal to optimize environmental control by providing optimal set-point strategies for each environmental parameter, taking into account mainly the long-term effects on the crop [85,3].

Physiological models together with actual real-time monitoring of the physiological status of the plants can lead to real-time control strategies. In practice, the measurement and identification of plant responses and the optimal control of the environment based on plant responses are necessary. This leads to the *speaking plant approach (SPA)* [86 and Section 5.3 above]. This approach can benefit from a large number of plant-oriented measurements. Over the years, SPA has been integrated with modern techniques from the field of artificial intelligence, with an aim towards integrated intelligent control. Knowledge-based systems play an important role towards this effort [87,88].

Important issues in all these highly computerized and automated systems is the quality of information provided by the sensors and the quality of decisions passed to the actuators. IT can provide the capability of developing intelligent control systems capable of self-examination. The combined information from different sensors can lead to quality classification of isolated information derived from specific sensors or actuators [89]. In this way, several fault-detection and diagnosis methodologies have been developed in greenhouse cultivation systems [90-93].

IGM: Integrated Greenhouse Management

Current major consumer concerns are direct exposure to traces of pesticides and other chemicals in food, and the indirect consequences to the environment, from the use of synthetic chemicals in the agricultural production process. Current research on consumer and environmental protection issues, and also on grower protection, has led to two basic solutions: biological products and integrated management. The grower has to comply with certain quality features in order to obtain certification for his products from specialized certification organizations. The actions that would lead to such compliance are the subject of continuous research and development of methods relevant to using natural and/or biological (not synthetic chemical) methods of plant protection, by the development of integrated pest management (IPM) techniques [94], and minimizing water and fertilizer use.

This integrated management of greenhouses has to be supervised and managed by an *integrated management system*, which is a specially designed program that leads to the development of certified products and provides the following:

- correct agricultural practices,
- employees' safety and hygiene,
- safety of products,
- traceability, and
- environment-friendly actions.

The main goal of integrated management of greenhouses is profitable production in an economically viable and environmentally conscious agricultural facility, which incorporates beneficial natural processes into modern cultivation practices. The benefits from the application of the system are:

- performance assurance for the entire cultivation and grower's income,
- decrease of environmental impacts of agricultural actions, and
- protection of the environment and agricultural products with fewer amounts of synthetic chemical compounds.

5.8.5 ICT Tools and Complete Products

The level of the technology from various aspects are:

- *System architectures*—Stand-alone controllers, PC-based, networked PC-based, and SCADA systems.
- *Languages and tools*—
  1. DOS-based; some systems still exist in 2004 due to reliability of this operating system and the wide availability of the PC platform.
  2. LabView or Matlab research setups, coupled to I/O command/control cards.
  3. Visual OOPS and Windows complete applications, usually used for the presentation and configuration functions of the controller part. Proprietary controllers are programmed in assembly, PLC types in ladder or similar, and advanced high-functionality systems in C.
  4. Decision support systems are developed using various programming platforms and technologies that reach higher levels of decision making (e.g., agents technologies for conflict management and optimization) and used as add-on systems to guide other lower-level but reliable systems, using specific DDE structures for data exchange.
- *Communications*—Wired with optical or magnetic isolation or RF at the system interconnection level from the sensor up to the controller and onward to the PC server. Internet connectivity has become a common feature for remote monitoring and control. Mobile connectivity is becoming an embedded technology to provide regular and alarm reporting to the "pocket of the user."
- *Greenhouse (GH) controllers*—Hardware aspects, autonomy aspects, advanced processing aspects, customizability and configurability issues, fixed-customizable-open IT systems for greenhouses.

5.8.6 Future IT Technologies for Greenhouse Production Management

The level we have reached in real field applications is advanced owing to efforts by researchers and companies involved in agricultural automation. These advances are becoming the mainstream technology; the cost is becoming lower and we see greenhouse automation including advanced features such as wireless sensors and actuators, distributed microcontrollers, main controllers supporting web cameras, remote supervisory systems with Internet connection, and, finally, remote support and troubleshooting networks. Knowledge networks are under development; these will remotely monitor the operation, assist the system or the grower in making critical decisions in risky situations (e.g., infections, nutrition problems in complex hydroponic recirculating systems), or to change the environment for a crop with unusual requirements. Special greenhouse units have been developed to become food-producing factories (e.g., leafy vegetables produced continuously in sealed chambers), fully equipped with tight environment control equipment and management systems with embedded knowledge.

References

1. Bot, G. P. A. 1991. Physical modelling of greenhouse climate. *Mathematical and Control Applications in Agriculture and Horticulture,* eds. Y. Hashimoto, and W. Day, 7-12. Oxford, UK: Pergamon Press.
2. Bakker, J. C., G. P. A. Bot, H. Challa, and N. J. van de Braak. 1995. *Greenhouse Climate Control: An Integrated Approach*. Wageningen, The Netherlands: Wageningen.
3. Jones, J. W., E. Dayan, L. H. Allen, H. Vankeulen, and H. Challa. 1991. A dynamic tomato growth and yield model (TOMGRO). *Trans. ASAE* 34: 663-672.
4. Challa, H., and G. van Straten.1993. Diurnal control in greenhouses. *The Computerized Greenhouse*. eds. Y. Hashimoto, G. P. A. Bot, W. Day, H.-J. Tantau, and H. Nonami, 119-137.San Diego, CA: Academic.
5. Aaslyng, J. M., N. Ehler, P. Karlsen, and E. Rosenqvist. 1999. Intelligrow: A component-based climate control system for decreasing greenhouse energy consumption. *Acta Horticulturae* 507: 35-42.
6. Bates, M. E., and D. L. Bubenheim. 1999. Applications of process control to plant-based life support systems. SAE Technical Paper No. 972359. Warrendale, PA: Society of Automotive Engineers.
7. Volk, T., B. Bugbee, and R. M. Wheeler. 1995. An approach to crop modeling with the energy cascade. *Life Support and Biosphere Sci*. 1: 119-127.
8. Marcelis, L. F. M., E. Heuvelink, and J. Goudriaan. 1997. Modelling biomass production and yield of horticultural crops: A review. *Sc. Horticulturae,* 83-104.
9. Ferentinos, K. P., A. Anastasiou, G. D. Pasgianos, K. G. Arvanitis, and N. Sigrimis. 2003. A decision support system as a tool to optimal water management in soilless cultures under saline conditions. *International ISHS Symposium on Managing Greenhouse Crops in Saline Environment.*
10. Sigrimis, N., K. G. Arvanitis, and G. D. Pasgianos. 2000. Synergism of high and low level systems for the efficient management of greenhouses. *Computers and Electronics in Agriculture* 29: 21-39.
11. Seginer, I. 1993. Crop models in greenhouse climate control. *Acta Horticulturae* 328: 79-97.
12. Albright, L. D., R. S. Gates, K. G. Arvanitis, and A. Drysdale. 2001. Environmental control for plants on Earth and in space. *IEEE Control Systems Magazine* 21(5): 28-47.
13. Gates, R. S., L. W. Turner, and D. G. Overhults. 1992. A survey of environmental controllers. *Trans. ASAE* 35: 993-998.
14. Albright, L. D. 1990. *Environment Control for Animals and Plants.* St. Joseph, MI: ASAE.
15. Young, P. C., W. Tych, and A. Chotai. 1991. Identification, estimation and control of glasshouse systems. *Mathematical and Control Applications in Agriculture and Horticulture,* eds. Y. Hashimoto, and W. Day, 33-40. Oxford, UK: Pergamon Press.

16. Chotai, A., P. C. Young, P. Davis, and Z. Chalabi. 1991. True digital control of glasshouse systems. *Mathematical and Control Applications in Agriculture and Horticulture.* eds. Y. Hashimoto, and W. Day, 41-46. Oxford, UK: Pergamon Press.
17. Young, P. C., A. Chotai, and W. Tych. 1993. Identification, estimation and true digital control of glasshouse systems. *The Computerized Greenhouse*, eds. Y. Hashimoto, G. P. A. Bot, W. Day, H.-J. Tantau, and H. Nonami, 3-50. Academic Press.
18. Åström, K., and T. Hägglund. 1998. *PID controllers: Theory, Design and Tuning.* Research Triangle Park, NC: ISA Publications.
19. Jones, P., J. W. Jones, L. H. Allen, and J. W. Mishoe. 1984. Dynamic computer control of closed environmental plant chambers: Design and verification. *Trans. ASAE* 27: 879-888.
20. Stanghellini, C., and W. T. M. van Meurs. 1992. Environmental control of greenhouse crop transpiration. *J. Agricultural Engineering Research* 51: 297-311.
21. Arvanitis, K. G., P. N. Paraskevopoulos, and A. A. Vernardos. 2000. Multirate adaptive temperature control of greenhouses. *Computers and Electronics in Agriculture* 26: 303-320.
22. Chao, K., and R. S. Gates. 1996. Design of switching control systems for ventilated greenhouses. *Trans. ASAE* 39: 1513-1523.
23. Phelan, R. M. 1977. *Automatic Control Systems*. Ithaca, NY: Cornell University Press.
24. Setiawan, A., L. D. Albright, and R. M. Phelan. 2000. Application of pseudo-derivative-feedback algorithm in greenhouse air temperature control. *Computers and Electronics in Agriculture* 26: 283-302.
25. Young, P. C., M. J. Lees, A. Chotai, W. Tych, and Z. S. Chalabi. 1994. Modelling and PIP control of a glasshouse microclimate. *Control Engineering Practice* 2: 591-604.
26. Lees, M. J., M. J. Taylor, A. Chotai, P. C. Young, and Z. S. Chalabi. 1996. Design and implementation of a Proportional-Integral-Plus (PIP) control system for temperature, humidity and carbon dioxide in a glasshouse. *Acta Horticulturae* 406: 115-123.
27. Smith, O. J. M. 1957. Closer control of loops with dead time. *Chemical Engineering Progress* 53: 217.
28. Sigrimis, N., K. G. Arvanitis, G. D. Pasgianos, and K. P. Ferentinos. 2002. Computer integrated management and intelligent control of greenhouses. *Environment Control in Biology* 40(1): 39-53.
29. Hashimoto, Y. 1997. Applications of artificial neural networks and genetic algorithms to agricultural systems. *Computers and Electronics in Agriculture* 18: 71-72.
30. Seginer, I., T. Boulard, and B. J. Bailey. 1994. Neural network models of the greenhouse climate. *J. Agricultural Engineering Research* 59: 203-216.
31. Seginer, I., Y. Hwang, T. Boulard, and J. Jones. 1996. Mimicking an expert greenhouse grower with a neural network policy. *Trans. ASAE* 39: 299-306.

32. Kok, R., R. Lacroix, G. Clark, and E. Taillefer. 1994. Imitation of a procedural greenhouse model with an artificial neural-network. *Canadian Agricultural Engineering* 36: 117-126.
33. Ferreira, P. M., E. A. Faria, and A. E. Ruano. 2002. Neural network models in greenhouse air temperature prediction. *Neurocomputing* 43: 51-75.
34. Frausto, H. U., and J. G. Pieters. 2004. Modelling greenhouse temperature using system identification by means of neural networks. *Neurocomputing* 56: 423-428.
35. Ferentinos, K. P., and L. D. Albright. 2002. Predictive neural network modeling of pH and electrical conductivity in deep-trough hydroponics. *Trans. ASAE* 45: 2007-2015.
36. Frick, J., C. Precetti, and C. A. Mitchell. 1998. Predicting lettuce canopy photosynthesis with statistical and neural network models. *J. American Society for Horticultural Science* 123: 1076-1080.
37. Seginer, I. 1997. Some artificial neural network applications to greenhouse environmental control. *Computers and Electronics in Agriculture* 18: 167-186.
38. Ferentinos, K. P. 2005. Biological engineering applications of feedforward neural networks designed and parameterized by genetic algorithms. *Neural Networks* 18: 934-950.
39. Goggos, V., and R. E. King. 2000. Qualitative-evolutionary design of greenhouse environment control agents. *Computers and Electronics in Agriculture* 26: 271-282.
40. Hashimoto, Y., H. Murase, T. Morimoto, and T. Torii. 2001. Intelligent systems for agriculture in Japan. *IEEE Control Systems Magazine* 21(5): 71-85.
41. Morimoto, T., K. Hatou, and Y. Hashimoto. 1996. Intelligent control for plant production system. *Control Engineering Practice* 4: 773-784.
42. Morimoto, T., T. Torii, and Y. Hashimoto. 1995. Optimal-control of physiological processes of plants in a green plant factory. *Control Engineering Practice* 3: 505-511.
43. Husmann, H. J., and H. J. Tantau. Integrated optimization of energy supply systems in horticulture using genetic algorithms. *Computers and Electronics in Agriculture* 31: 47-59.
44. Caponetto, R., L. Fortuna, G. Nunnari, L. Occhipinti, and M. G. Xibilia. 2000. Soft computing for greenhouse climate control. *IEEE Transactions on Fuzzy Systems* 8: 753-760.
45. Murase, H. 2000. Finite element inverse analysis using a photosynthetic algorithm. *Computers and Electronics in Agriculture* 29: 115-123.
46. Kurata, K., and N. Eguchi. 1990. Machine learning of fuzzy rules for crop management in protected cultivation. *Trans. ASAE* 33: 1360-1368.
47. Salgado, P., J. B. Cunha, and C. Couto. 1998. A fuzzy identification and controller for the agricultural greenhouse. 7th *International Conference on Computers in Agriculture.* St. Joseph, MI: ASAE.
48. Gates, R. S., K. Chao, and N. Sigrimis. 2001. Identifying design parameters for fuzzy control of staged ventilation control systems. *Computers and Electronics in Agriculture* 31: 61-74.

49. Chao, K., R. S. Gates, and N. Sigrimis. 2000. Fuzzy logic controller design for staged heating and ventilating systems. *Trans. ASAE* 43: 1885-1894.
50. Sigrimis, N. A., K. G. Arvanitis, and R. S. Gates. 2000. A learning technique for a general purpose optimizer. *Computers and Electronics in Agriculture* 26: 83-103.
51. Krug, H., and H.-P. Liebig. 1980. Diurnal thermoperiodism of the cucumber. *Acta Horticulturae* 118: 83-94.
52. Langhans, R. W., M. Wolfe, and L. D. Albright. 1981. Use of average night temperatures for plant growth for potential energy savings. *Acta Horticulturae* 115: 31-37.
53. Miller, W. B., R. W. Langhans, and L. D. Albright. 1985. Plant growth under average day/night temperatures. *Acta Horticulturae* 174: 313-320.
54. Both, A. J., L. D. Albright, and R. W. Langhans. 1997. Coordinated management of daily PAR integral and carbon dioxide for hydroponic lettuce production. *Acta Horticulturae* 456: 45-51.
55. Saffell, R. A., and B. Marshall. 1983. Computer control of air temperature in a glasshouse. *J. Agricultural Engineering Research* 28: 469-478.
56. De Koning, A. N. M. 1988. An algorithm for controlling the average 24-hour temperature in glasshouses. *J. Horticultural Science* 63: 473-477.
57. De Koning, A. N. M. 1990. Long term temperature integration of tomato: Growth and development under alternating temperature regimes. *Scientia Horticulturae* 45: 117-127.
58. Hooper, A. W., and P. F. Davis. 1988. An algorithm for temperature compensation in a heated greenhouse. *Computers and Electronics in Agriculture* 3: 251-262.
59. Timmons, M. B., and R. S. Gates. 1987. Relative humidity as a ventilation control parameter in broiler housing. *Trans. ASAE* 30: 1111-1115.
60. Timmons, M. B., R. S. Gates, R. W. Bottcher, T. A. Carter, J. T. Brake, and M. J. Wineland. 1995. Simulation analysis of a new temperature control method for poultry housing. *J. Agricultural Engineering Research* 62: 237-245.
61. Gates, R. S., M. B. Timmons, D. G. Overhults, and R. W. Bottcher. 1997. Fuzzy reasoning for environment control during periods of heat stress. *Proc. of the Fifth International Symposium, Livestock Environment,* 553-562. St Joseph, MI: ASAE.
62. Marsh, L. S., and L. D. Albright. 1991. Economically optimum day temperature for greenhouse hydroponic lettuce production Part 1: A computer model. *Trans. ASAE* 34: 550-556.
63. Marsh, L. S., and L. D. Albright. 1991. Economically optimum day temperature for greenhouse hydroponic lettuce production Part 2: Results and simulations. *Trans. ASAE* 34: 557-562.
64. Seginer, I., G. Shina, L. D. Albright, and L. S. Marsh. 1991. Optimal temperature setpoints for greenhouse lettuce. *J. Agricultural Engineering Research* 49: 209-226.

65. Tantau, H.-J. 1998. Energy saving potential of greenhouse climate control. *Mathematics and Computers in Simulation* 48: 93-101.
66. Sigrimis, N., A. Anastasiou, and N. Rerras. 2000. Energy saving in greenhouse using temperature integration: A simulation survey. *Computers and Electronics in Agriculture* 26: 321-341.
67. Bot, G. P. A. 2001. Developments in indoor sustainable plant production with emphasis on energy saving. *Computers and Electronics in Agriculture* 30: 151-165.
68. Korner, O., and H. Challa. 2003. Design for an improved temperature integration concept in greenhouse cultivation. *Computers and Electronics in Agriculture* 39: 39-59.
69. Albright, L. D., A.-J. Both, and A. J. Chiu. 2000. Controlling greenhouse light to a consistent daily integral. *Trans. ASAE* 43: 421-431.
70. Ferentinos, K. P., L. D. Albright, and D. V. Ramani. 2000. Optimal light integral and carbon dioxide concentration combinations for lettuce in ventilated greenhouses. *J. Agricultural Engineering Research* 77: 309-315.
71. Korner, O., and H. Challa. 2003. Process-based humidity control regime for greenhouse crops. *Computers and Electronics in Agriculture* 39: 173-192.
72. van Straten, G., H. Challa, and F. Buwalda. 2000. Towards user accepted optimal control of greenhouse climate. *Computers and Electronics in Agriculture* 26: 221-238.
73. van Straten, G., L. G. van Willigenburg, and R. F. Tap 2002. The significance of crop co-states for receding horizon optimal control of greenhouse climate. *Control Engineering Practice* 10: 625-632.
74. Chalabi, Z. S., B. J. Bailey, and D. J. Wilkinson. 1996. A real-time optimal control algorithm for greenhouse heating. *Computers and Electronics in Agriculture* 15: 1-13.
75. Lacroix R, and R. Kok. 1999. Simulation-based control of enclosed ecosystems—A case study: Determination of greenhouse heating setpoints. *Canadian Agricultural Engineering* 41: 175-183.
76. Gieling, T., H. J. J. Janssen, G. van Straten, and M. Suurmond. 2000. Identification and simulated control of greenhouse closed water supply systems. *Computers and Electronics in Agriculture* 26: 361-374.
77. Stanghellini, C. 1987. Transpiration of greenhouse crops, an aid to climate management. PhD diss. Wageningen, The Netherlands: Wageningen Agricultural University.
78. Sigrimis, N., K. G. Arvanitis, G. D. Pasgianos, and K. Ferentinos. 2001. Hydroponics water management using adaptive scheduling with an on-line optimiser. *Computers and Electronics in Agriculture* 31: 31-46.
79. Gal, S., A. Angel, and I. Seginer. 1984. Optimal control of greenhouse climate: methodology. *European J. Operational Research* 17: 45-56.
80. Seginer, I., and R. W. McClendon. 1992. Methods for optimal control of the greenhouse environment. *Trans. ASAE* 35: 1299-1307.

81. Pasgianos, G. D., K. G. Arvanitis, P. Polycarpou, and N. Sigrimis. 2003. A nonlinear feedback technique for greenhouse environmental control. *Computers and Electronics in Agriculture* 40: 153-177.
82. Linker, R., P. O. Gutman, and I. Seginer. 1999. Robust controllers for simultaneous control of temperature and CO_2 concentration in greenhouses. *Control Engineering Practice* 7: 851-862.
83. Ferentinos, K. P., K. G. Arvanitis, S. Hontas, D. Lambrou, and N. Sigrimis. 2004. A multi-agent system for integrated production in greenhouse hydroponics. *AgEng 2004, Leuven, Belgium,* accepted for publication.
84. King, R. E., and N. Sigrimis. 2001. Computational intelligence in crop production. *Computers and Electronics in Agriculture* 31: 1-3.
85. Jolliet, O. 1994. HORTITRANS, a model for predicting and optimizing humidity and transpiration in greenhouses. *J. Agricultural Engineering Research* 57: 23-37.
86. Morimoto, T., and Y. Hashimoto. 2000. An intelligent control for greenhouse automation, oriented by the concepts of SPA and SFA–An application to a post-harvest process. *Computers and Electronics in Agriculture* 29: 3-20.
87. Chao, K., R. S. Gates, and R. G. Anderson. 1998. Knowledge-based control systems for single stem rose production Part I: Systems analysis and design. *Trans. ASAE* 41: 1153-1161.
88. Anastasiou, A., N. Rerras, and N. Sigrimis. 1998. A knowledge based SCADA system for agricultural process control. *Proc. of International Federation of Automatic Control—CAEA'98,* eds. N. Sigrimis, and P. Groumpos, 163-168. Oxford, UK: Pergamon.
89. Ferentinos, K. P., and L. D. Albright. 2003. Fault detection and diagnosis in deep-trough hydroponics using intelligent computational tools. *Biosystems Engineering* 84: 13-30.
90. Beaulah, S. A., and Z. S. Chalabi. 1997. Intelligent real-time fault diagnosis of greenhouse sensors. *Control Engineering Practice* 5: 1573-1580.
91. Linker, R., P. O. Gutman, and I. Seginer. 2002. Observer-based robust failure detection and isolation in greenhouses. *Control Engineering Practice* 10: 519-531.
92. Ferentinos, K. P., L. D. Albright, and B. Selman. 2003. Neural network-based detection of mechanical, sensor and biological faults in deep-trough hydroponics. *Computers and Electronics in Agriculture* 40: 65-85.
93. Linker, R., and I. Seginer. 2003. Water stress detection in a greenhouse by a step change of ventilation. *Biosystems Engineering* 84: 79-89.
94. Antignus, Y., 2001. Manipulation of wavelength-dependent behaviour of insects: An IPM tool to impede insects and restrict epidemics of insect-borne viruses. *Virus Research* 71: 213-220.