8 Crop growth models for greenhouse climate control

H. Challa

8.1 Introduction

In the last 20 years various different models have been developed to describe and explain crop growth under various conditions. These explanatory models have mainly been used for research to elucidate the often quite complex relations between crop environment and yield. Their practical significance has been mainly through this improved understanding, rather than the direct use of their output.

Models, however, basically do have great potential for practical use in agriculture in general (Penning de Vries, 1983) and in horticulture in particular (Challa, 1985; 1988). In general, their use (which is still very limited) is in the field of decision-making at the three levels of farmer's involvement that are usually distinguished, depending on the decision horizon (Table 8). Spedding and van Keulen give examples of the use of models for strategic decisions (Chapters 13 and 15, respectively). Penning de Vries (1983) mentions models being used for decision support at the operational level in the case of pest management and irrigation. Decisions about process control, an important item in greenhouse culture, are usually considered within the framework of the operational decisions. In my opinion, however, process control should be considered as a special category (Table 8). The principle difference between operational decisions and process control is that the latter lacks human interference. The operator checks the process from time to time and may adjust the control procedure, but the actual control is delegated to the control system.

The main reason we need to use models to control biological systems is because of the difficulty of measuring the relevant processes directly and the inherent need to interpret on-line measurements in the terms desired. In the second place it is often quite difficult to predict a required action in order to obtain a desired reaction. Process control, as described here, is characteristic for protected cultiva-

Table 8. Decision levels and horizons and the involvement of the manager.

Decision level	Horizon	Involvement of manager
Strategic	1 – many years	+ +
Tactical	≤ 1 year	+ +
Operational	days – months	+
Process control	≤ 24 h	–

tion, though with the introduction of fertigation, horticulture in the open air will also have to deal with it to a certain extent.

In this chapter the need to use crop growth models and their potential in relation to the optimization of greenhouse climate control will be considered. Certain characteristics of models constructed for this purpose and difficulties related to the practical implementation of strategies of optimization in control systems will be discussed. The required interaction with the grower and the grower's knowledge wil be highlighted. The net financial response to the control of CO_2 pressure and greenhouse temperature and its sensitivity to a number of relevant parameters will be elucidated.

8.2 Control in greenhouses

The greenhouse shelter profoundly modifies the climatic conditions inside the greenhouse. This is true not only for temperature, but also for CO_2 pressure, radiation and water vapour pressure. The temperature inside the greenhouse is usually higher than that outside. Apart from the energy supplied from the heating system, this rise in temperature is caused by radiative energy from the sun being trapped in the greenhouse because of a strong decrease in turbulent air exchange with the outside air and a decreased long-wave exchange with the sky (Bot, 1983). In an equilibrium situation the energy supplied to the greenhouse is released to the environment by convection and ventilation (sensible and latent heat). In the light, CO_2 is assimilated by the crop and this loss is compensated for by exchange with outside air and additional CO_2 supplied by the grower. The greenhouse cover transmits only part of the radiation, and the reduction of light can be substantial especially when the sun is at a low angle (Bot, 1983). Furthermore, crop transpiration causes the water vapour pressure inside the greenhouse to be higher than that outside.

The greenhouse climate can be controlled by means of a number of actuators (Figure 36), the major ones being: heating pipes (*p*), ventilators (*v*) and a CO_2 supply system (*c*). In addition, the root zone can be controlled with respect to temperature and, in the case of soilless cultivation, the mineral composition and the osmotic potential of the nutrient solution. Greenhouse culture may be considered as the most intensively managed form of agriculture.

Originally, climate control of greenhouses was primitive: only extreme conditions were avoided and the actuators were operated manually. Later, automation was introduced primarily to save labour. Advances in electronics enabled more refined control procedures to be developed, e.g. to regulate set-points for ventilation and heating in accordance with the prevailing radiation level. In the Netherlands these improved procedures were primarily based on a systematic survey of common practice of climate control among 'good' growers (Strijbosch & van de Vooren, 1975), whereas scientific research contributed more to improved average regimes over longer periods of time. When digital computers replaced electronic controllers this was mainly for reasons of efficiency: one controller was able to

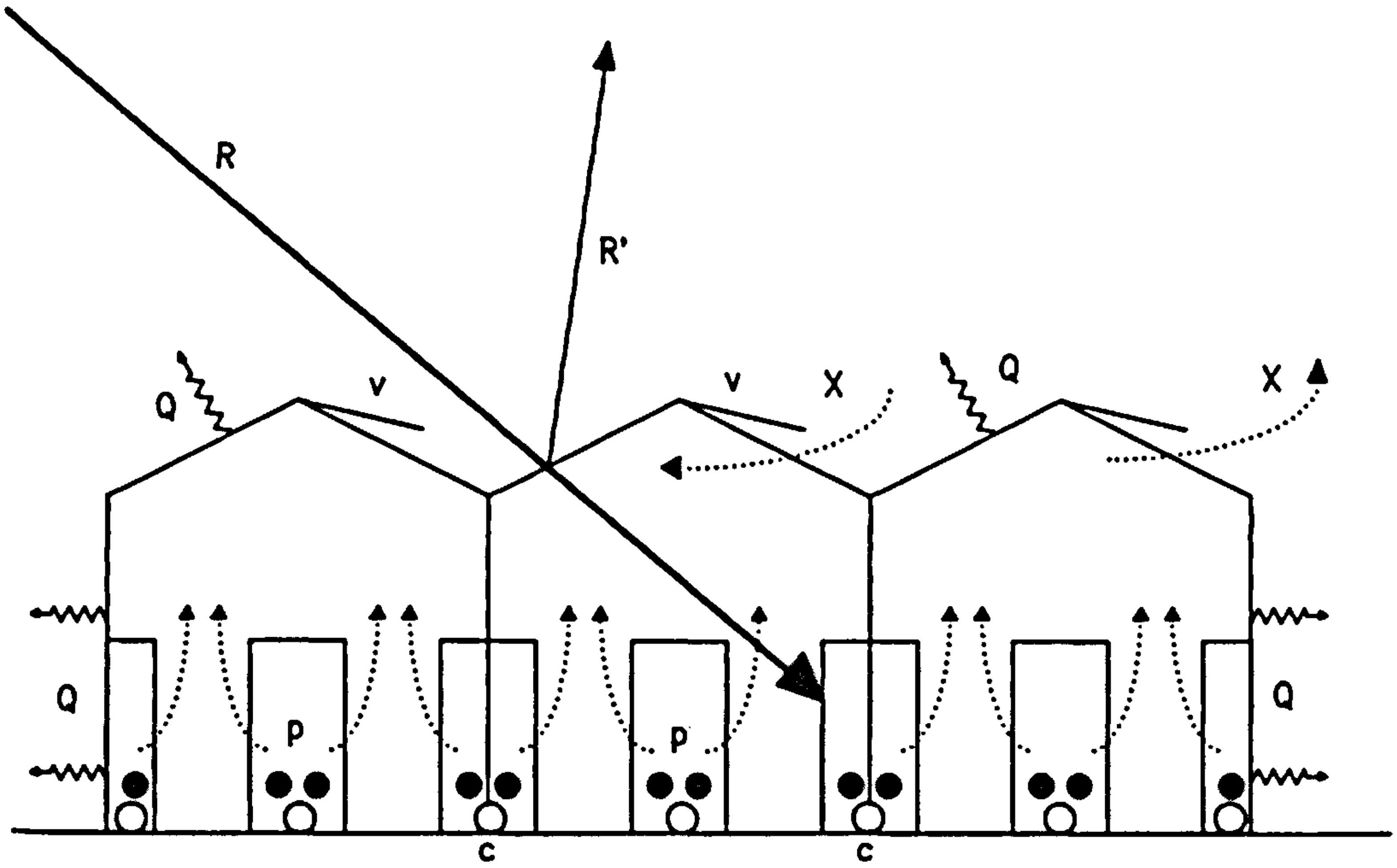


Figure 36. The major actuators for the control of greenhouse climate and the physical processes that are involved. Actuators: ventilators (*v*), heating pipes (*p*, solid circles) and CO_2 supply (*c*, open circles). Processes: transmission of short-wave radiation (*R*) from the sky, air exchange (*X*), including exchange of CO_2 and water vapour, and convective energy loss (*Q*) through the greenhouse cover.

handle a number of greenhouse compartments and this was cheaper than having an electronic controller for each compartment. Other advantages of the use of computers for climate control that played a role in this change were the possibilities of registering the actual climatic conditions and the greater flexibility that allowed other control procedures to be implemented easily, without changing the hardware. More recently, requirements for data exchange between the process control system and the management computer system have also promoted the widespread use of computers for climate control.

In spite of many improvements in hardware and software, little has changed in the underlying philosophy. The control algorithms are still primarily derived from the experience of growers and owe little to scientific research. The basic scheme followed (Figure 37) is that set-points for heating and ventilation are obtained using a classic, usually a *PI* (proportional-integrating) control algorithm (Udink ten Cate, 1980). This control loop (Loop 1) is the inner control loop with the fastest response time. The set-points are selected according to simple procedures (Loop 2), essentially characterized by separate heating and ventilation set-points for day and for night and a somewhat clumsy procedure for controlling air humidity because there is no separate actuator for its control (Anonymous, 1987). The procedures followed at this level are (as mentioned above) primarily derived from the experience of growers. The grower adjusts the control system occasionally (Loop 3) for best performance, on the basis of his observations of the crop and his knowledge of crop requirements. This knowledge

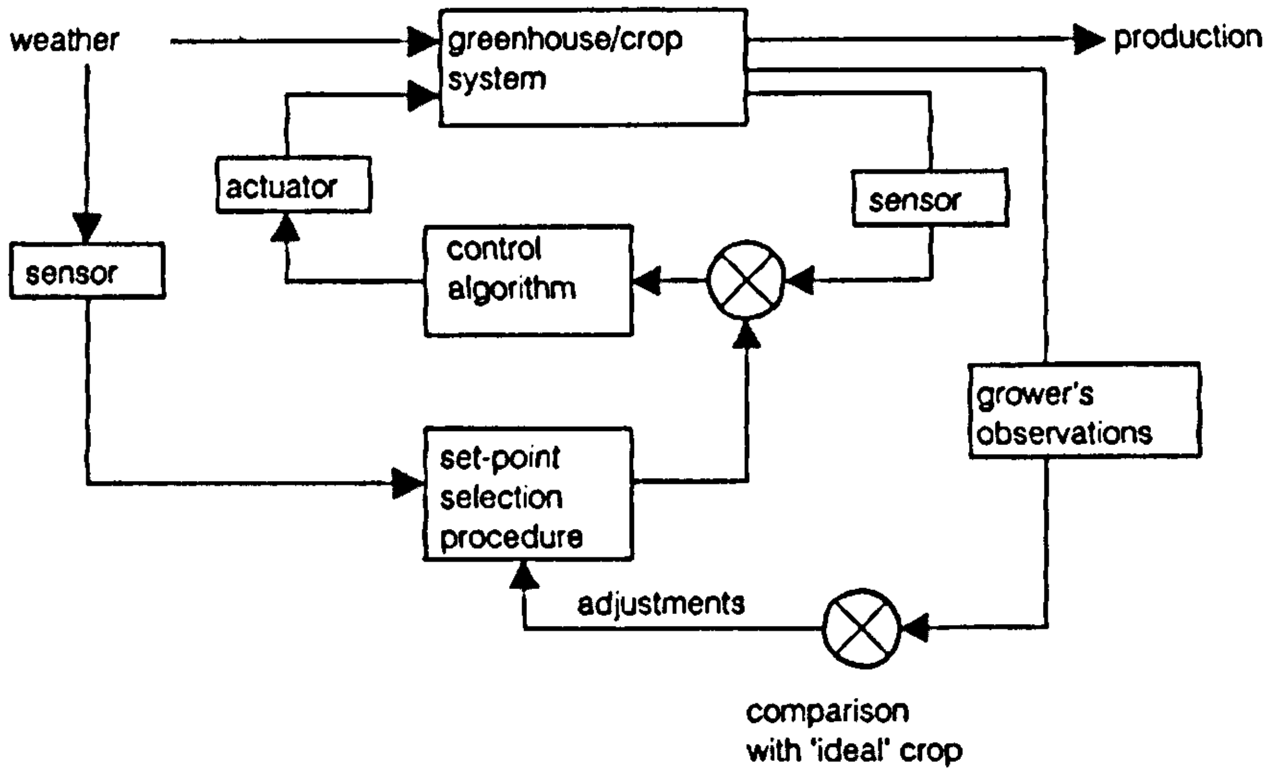


Figure 37. Schematic representation of climate control in greenhouses. There are three loops with different time coefficients: the fast inner loop for maintaining set-points, a second loop where set-points are established and a third loop in which the grower is involved and where the algorithms can be adjusted for optimal performance.

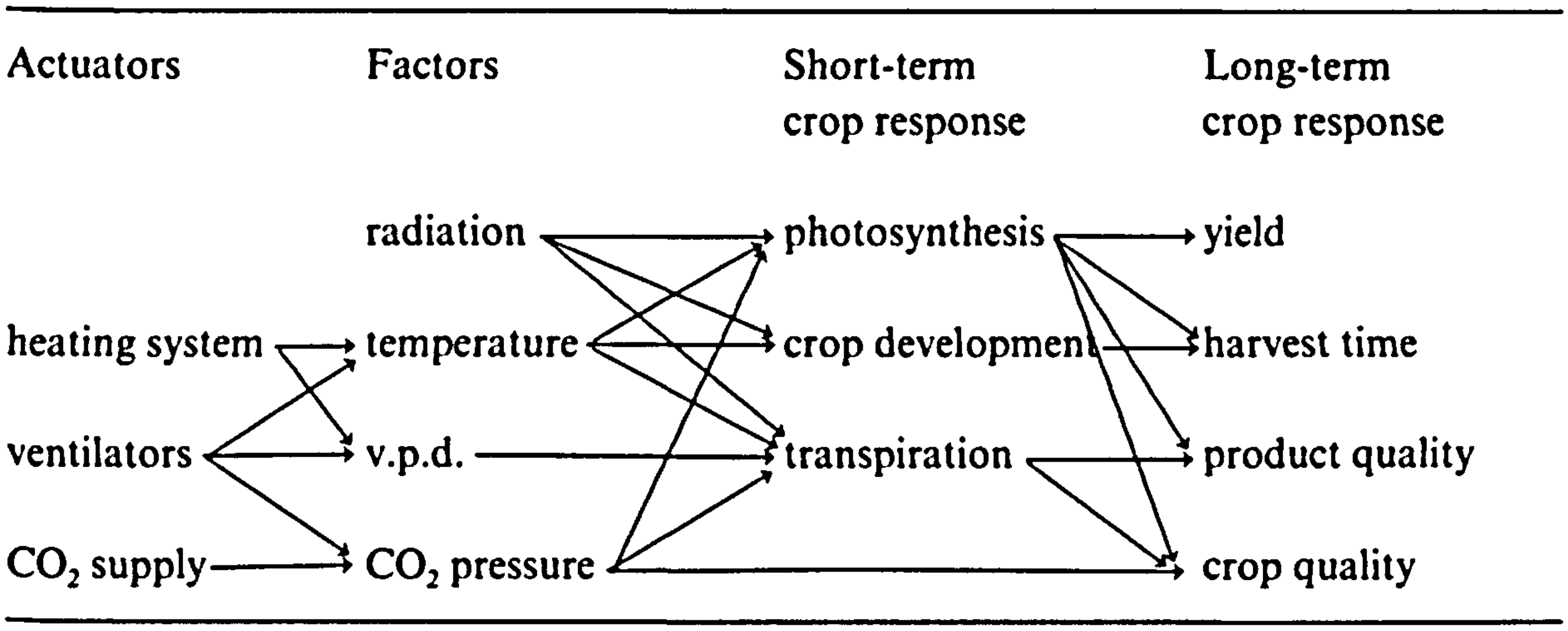
is a blend of results from scientific research and own experience. The grower's decisions in Loop 3 may be considered as operational decisions, whereas Loops 1 and 2 belong to 'process control'.

8.3 Optimal control

As pointed out above, the basic principles of climate control have evolved pragmatically. Hence, although growers are able to grow their crops very well with their current techniques it is unlikely that they achieve their goal(s) in an optimal way (Challa et al., 1988). As will be discussed later in this chapter, a number of objectives play a role in relation to climate control. Below, however, I will focus on one, important aspect, namely the question of optimal use of inputs in relation to the expected output, within the time-scale ≤ 24 h.

The grower's great handicaps at this control level are his inability to observe the fast response of crops to the instantaneous conditions and the very indirect and complicated relation between the setting of his control system, the factors to be controlled and the processes with a fast (≤ 24 h) and a slow (days to weeks) response time (Table 9). The main problem of climate control in greenhouses is that there is no simple relation between actuators, environmental factors inside the greenhouse, short-term crop response and long-term results. The system consists of strongly interacting processes and subsystems. In addition, the grower is dealing with a control system which, on the one hand can increase economic yield (e.g. by raising temperature or CO_2 pressure), but on the other hand can raise the cost of operation. Optimization of the system is achieved when conditions are such that further increase of the input of relevant cost factors is just counterbalanced by the increase in yield (Figure 38). The question of optimization, of course, is

Table 9. Some important relations between actuators, factors and short- and long-term crop response (v.p.d. = water vapour pressure deficit of the greenhouse air).



relevant when variations in the input give rise to variations in the associated costs (Seginer, 1980). In the case of greenhouse climate control, the CO_2 pressure and temperature and humidity of the air are the major factors to be considered. The optimization problem for CO_2 and temperature is schematically depicted in Figure 39 and will be worked out below. As Figure 39 shows, crop photosynthesis responds to radiation, CO_2 and temperature and there is a strong interaction at the control level as well as at the process level.

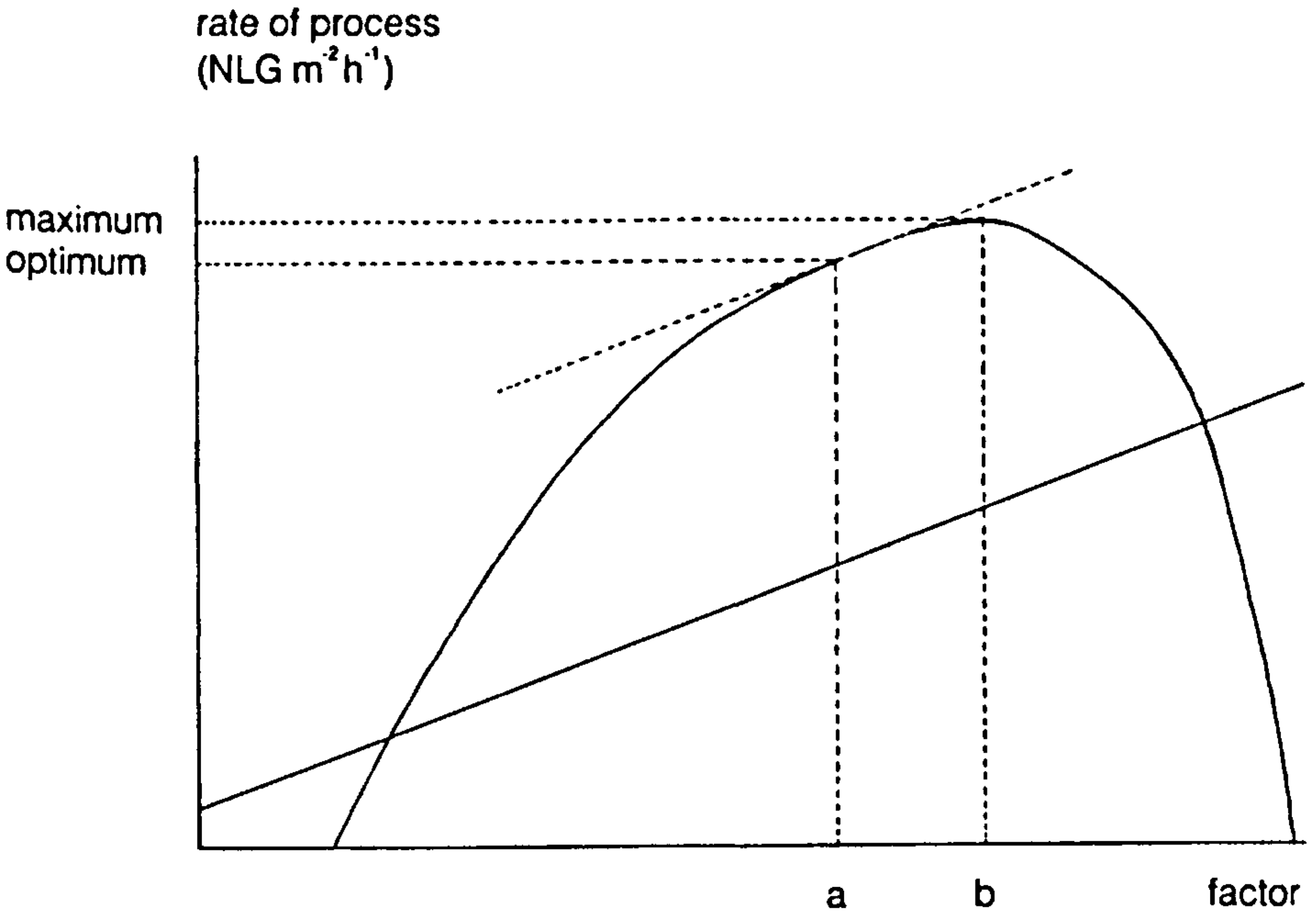


Figure 38. The principle of optimization explained with one input factor related to the rate of one process (optimum curve) and the rate of input requirement (solid straight line), both expressed in financial terms. The break-even point, where the increase of the cost of the input factor equals the increase of the financial output is obtained at an input level *a*. At an input level *b* the maximum output is obtained, which, however, gives rise to a lower net financial output than an input *a*.

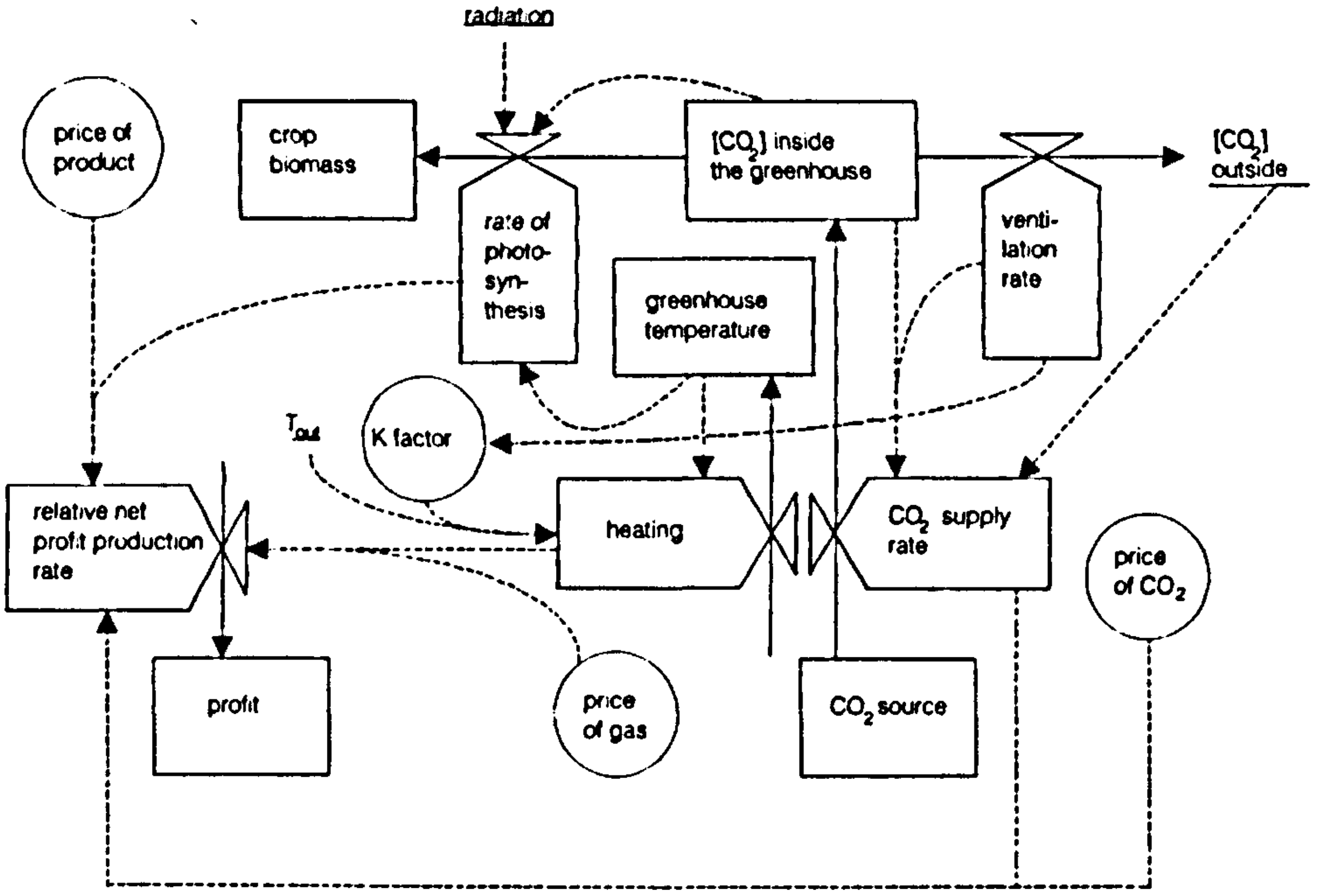


Figure 39. The optimization process with CO_2 and temperature control in greenhouses.

Although other factors such as crop water-status, or sink activity may limit crop performance, there are good arguments for considering crop gross photosynthesis as the key process in relation to short-term optimization of greenhouse climate control (Challa, 1989). According to Penning de Vries & van Laar (1982) the rate of production of a crop can be described by

$$Y_f = f_{wo}\,\alpha\,(P_g - R_m)/C_{dm} \qquad \text{Equation 18}$$

where

Y_f = rate of production (harvestable fresh weight) $(g\,m^{-2}\,h^{-1})$
f_{wo} = fraction of assimilates diverted to harvestable product $(g\,g^{-1})$
α = conversion efficiency CH_2O to structural dry weight $(g\,g^{-1})$
P_g = gross photosynthesis rate (CH_2O units) $(g\,m^{-2}\,h^{-1})$
R_m = rate of maintenance respiration (CH_2O units) $(g\,m^{-2}\,h^{-1})$
C_{dm} = dry matter content of the product $(g\,g^{-1})$

To optimize the environmental factors with respect to the expected net financial output, it suffices to consider only differences in yield, ΔY_f in relation to variations in the relevant inputs (Challa & Schapendonk, 1986)

$$\Delta Y_f = f_{wo}\,\alpha\,\Delta P_g/C_{dm} \qquad \text{Equation 19}$$

provided that R_m is independent of the factors considered. The factors involved are CO_2 pressure, air temperature and air humidity and it is clear that temperature does affect the rate of maintenance respiration. A reasonable approach, however, is to accept the principle that, in the long term, a grower wants to achieve a given average temperature suitable for the crop, and in that case short-term variations in maintenance respiration will be averaged out in the long term. Therefore, these effects have to be neglected here. Likewise, although it is well known that the fraction of assimilates diverted to harvestable product (f_{wo}) may change, for example, with changing climatic conditions (Evans, Chapter 5), it is assumed here that these are reactions to the average climatic conditions and therefore play a negligible role in short-term control. Later in this chapter the relation between short- and long-term control will be considered.

Hence, differences in the rate of gross photosynthesis (P_g) multiplied by a conversion factor ($f_{wo}\ \alpha/C_{dm}$) and multiplied by the expected price should be evaluated financially in relation to the associated differences in the rate of consumption of energy and CO_2. In other words, the rate of financial output minus the rate of financial input of the factors considered, called the relative net profit production rate, *RNPPR* (Challa & Schapendonk, 1986), should be maximized, where

$$r_{vn} = \mathrm{d}(V_p - V_i)/\mathrm{d}t \qquad \text{Equation 20}$$

where

r_{vn} = relative net profit production rate (NLG $m^{-2}\ h^{-1}$)
V_p = the economic value of dry matter produced (NLG m^{-2})
V_i = the economic value of the inputs considered (NLG m^{-2})
t = time (h)

In Equation 20 those cost factors that are independent of the inputs considered are ignored, because they do not play a role in the optimization problem considered here. Therefore, values of *RNPPR* cannot be used to evaluate the actual profit to the grower.

In an earlier paper (Challa & Schapendonk, 1986) only the factor CO_2 pressure was considered. Here I propose to elaborate the discussion by introducing temperature control in the optimization, because it interferes strongly with the control of CO_2 pressure as well as with the response of the crop to CO_2. Although the control of air humidity certainly deservers attention it will be ignored here, because the effects on crop performance are too little understood and therefore cannot be handled quantitatively at present. Air humidity will therefore be considered here primarily as one of the factors that should be dealt with in the context of other objectives that should be involved in the overall management of greenhouse climate control, as will be discussed later.

To maximize *RNPPR* in relation to the inputs considered, it is necessary to calculate the instantaneous rates of P_g, CO_2 supply and of energy consumption in relation to the environmental factors inside and outside the greenhouse and the relevant greenhouse properties. Dynamic models that predict crop photosynthesis (Challa, 1989) and greenhouse behaviour (Bot, 1983) have been developed to do this. These models have to be integrated because the greenhouse and the crop are interacting systems: the greenhouse modifies the environment of the crop and the crop interferes in the CO_2, water vapour and energy budgets of the greenhouse.

Optimizing control algorithms will have to deal with dynamic aspects of the system: optimal set-points in a stationary situation may differ from optimal set-points under varying conditions, because the way in which the desired set-points are arrived at and the time required to realize those conditions play an important role (van Henten, 1989).

Although maximization of *RNPPR* is important in terms of economic operation of the greenhouse, it neither should nor can be the only criterion for climate control. Instead it should be considered as a fine tuning, at a level of refinement that the grower can have no actual knowledge of. This aspect of optimization should therefore fit into a wider framework that involves other objectives. Later in this chapter I will come back to this point.

8.4 The model

I now propose to examine the response of *RNPPR* to temperature and CO_2 pressure inside the greenhouse in a static approach, using cucumber as an example. The benefit of this approach is that insight is obtained in the characteristics of the response surface and in the order of magnitude of gains that could be obtained through optimization at this level. Because of the exploratory character of this study, rough approximations are made to account for the behaviour of the greenhouse. The model used to describe the instantaneous rate of crop photosynthesis was essentially derived from SUCROS87 (Spitters et al., 1989) but extended with a much more elaborate version of the module for leaf photosynthesis developed by Farquhar et al. (1980). This detailed, biochemical model of leaf photosynthesis is able to deal adequately with the combined effects of CO_2 pressure and temperature on the rate of gross CO_2 assimilation of a leaf (Berry & Raison, 1981; Farquhar & von Caemmerer, 1982; Schapendonk & Brouwer, 1985).

The approach adopted by Farquhar and colleagues was used and their parameters were adopted in order to obtain the response of leaf photosynthesis to temperature (Figure 40). This response follows the well-known optimum curve, which is most pronounced when irradiation and CO_2 pressure are high. The temperature for maximum photosynthesis is a function of radiation and CO_2 pressure. At low radiation and CO_2 pressure maximum photosynthesis is observed at low temperatures. It should, however, be noticed that in the low temperature range (< 17 °C) the model overestimates leaf photosynthesis for cucumber, because certain processes are not considered in the model (data not shown). This discrepancy is probably caused by changes in the membrane configuration at low temperature, a reaction that is characteristic of thermophylic plants such as cucumber (Berry & Björkman, 1980).

The distribution of light interception within the crop and the integration of leaf photosynthesis over crop height was calculated according to SUCROS87 (Spit-

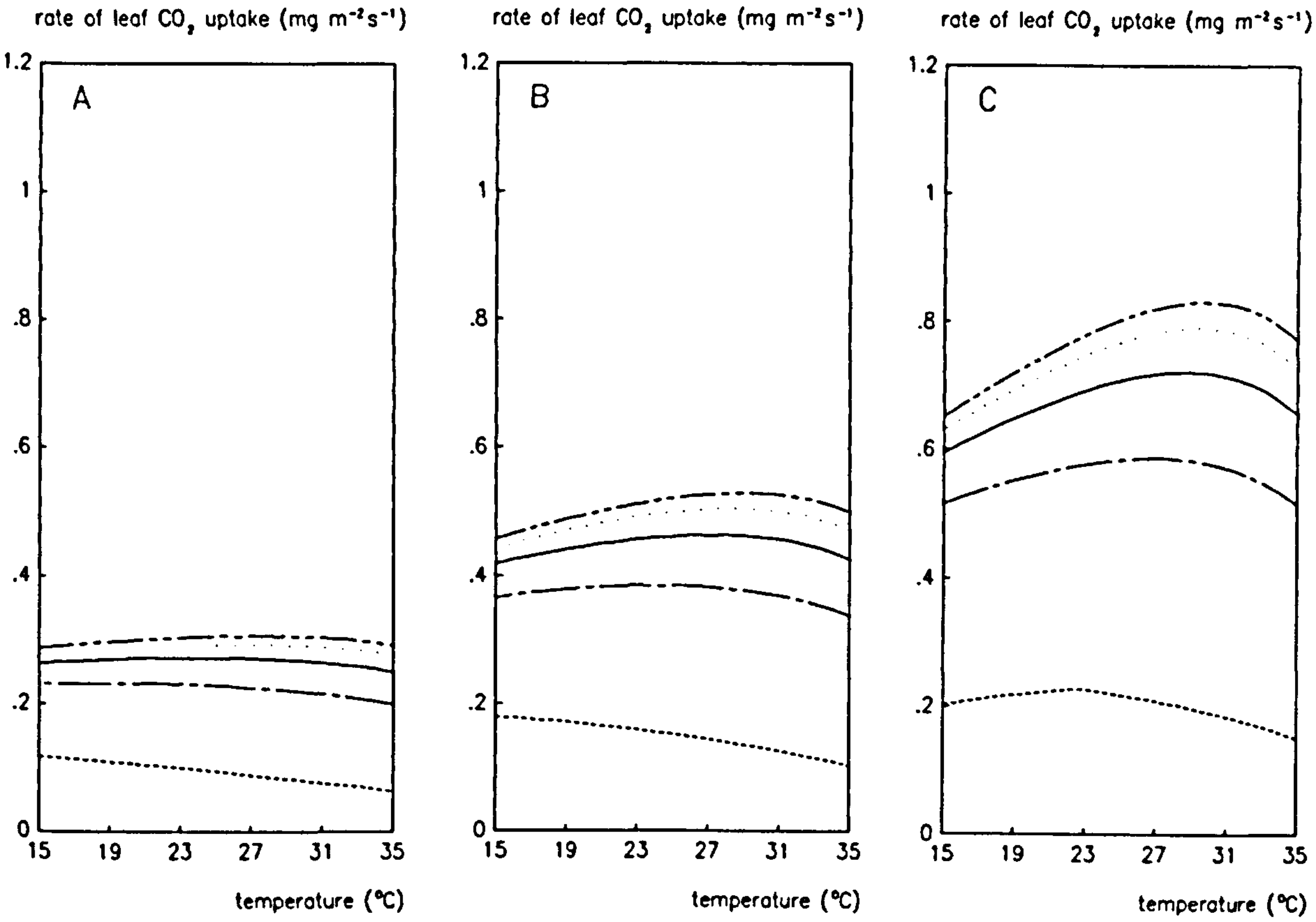


Figure 40. Simulated rate of gross photosynthesis of a single leaf as function of temperature at photosynthetically active radiation of 25 W m^{-2} (A), 50 W m^{-2} (B) and 100 W m^{-2} (C). CO_2 pressures are: (---) 10 Pa; (— — —) 32.5 Pa; (———) 55 Pa; (···) 77.5 Pa and (— — — —) 100 Pa. Absorption coefficient of leaf = 0.8. Other parameters are given in Table 10.

ters et al., 1989). For illustration, fixed values were selected here for the height of the sun and the fraction of diffuse radiation (Table 10). The response of the rate of crop photosynthesis to CO_2 pressure and temperature essentially resembles that of individual leaves (Figure 41). Apart from the absolute levels the main differences are observed in the response to temperature at high radiation, a difference that may be attributed mainly to a lower average irradiation of leaves in the crop situation. The effect of CO_2 pressure predominates but the effect of temperature cannot be ignored, especially at high CO_2 concentrations.

The rate of CO_2 supply (C_s) required to maintain a certain CO_2 pressure inside the greenhouse depends on the pressure difference with the outside air, the rate of CO_2 uptake by the crop and the air exchange rate which is used here as an input parameter, but, of course, in reality is related in a complicated way to ventilator opening and various other conditions (Kozai & Sase, 1978; Bot, 1983)

Table 10: List of parameter values used for the model calculations, and abbreviations and symbols used in this chapter.

Symbol	Meaning	Value	Units
–	chlorophyll per unit leaf area	0.45	g m^{-2}
–	CO_2 resistance stomatal + boundary layer	120	s m^{-1}
–	combustion energy of gas	35.2	MJ m^{-3}
–	concentration of enzyme sites in chlorophyll	87.0	μmol g^{-1}
–	conversion PAR to quanta	4.59	μE W^{-1}
–	dark respiration at 25°C	1.1	μmol m^{-2}s^{-1}
–	price of CO_2	0.20	NLG kg^{-1}
–	price of fuel (natural gas)	0.20	NLG m^{-3}
–	price of product (fresh weight)	0.004	NLG g^{-1}
–	turnover number of RuP2 carboxylase	2.5	s^{-1}
A_c	rate of CO_2 assimilation by the crop	–	g m^{-2} h^{-1}
C_o	CO_2 pressure of outside air	34	Pa
C_i	CO_2 pressure inside the greenhouse	–	Pa
C_s	rate of CO_2 supply	–	g m^{-2} h^{-1}
C_{dm}	dry matter content	0.035	g g^{-1}
d	density of CO_2	1800	g m^{-3}
e	efficiency heating system	0.9	J J^{-1}
f_{dif}	fraction of diffuse radiation	0.5	J J^{-1}
f_{wo}	fraction of dry weight in harvestable product	0.7	g g^{-1}
h	average height of greenhouse	3	m
l_{la}	leaf area index	3	m^2 m^{-2}
K	energy transfer coefficient (floor area basis)	–	J K^{-1} m^{-2} s^{-1}
K'	K factor at $\Phi = 0$	7	J K^{-1} m^{-2} s^{-1}
K_c	Michaelis-Menten constant for CO_2	31	Pa
K_o	Michaelis-Menten constant for O_2	15.5	Pa
NLG	Netherlands Guilder ($\approx$ 0.5 USD)		
P	pressure of the air	10^5	Pa
P_g	gross photosynthesis rate (CH_2O units)	–	g m^{-2} h^{-1}
Q	energy consumption for heating of greenhouse	–	J m^{-2} h^{-1}
R_g	global radiation inside the greenhouse	–	J m^{-2} s^{-1}
R_m	rate of maintenance respiration (CH_2O units)	–	g m^{-2} h^{-1}
RNPPR	relative net profit production rate (r_{vn})	–	NLG m^{-2} h^{-1}
r_{vn}	relative net profit production rate	–	NLG m^{-2} h^{-1}
t	time	–	h
T_i	temperature inside the greenhouse	–	°C
T_o	temperature outside the greenhouse	–	°C
V_{co}	V_{omax}/V_{cmax}	0.21	–
V_{cmax}	maximum rate of carboxylase reaction	–	μmol s^{-1}
V_i	economic value of the inputs considered	–	NLG m^{-2}

Table 10 continued

Symbol	Meaning	Value	Units
V_{omax}	maximum rate of oxygenase reaction	–	$\mu mol\ s^{-1}$
V_p	economic value of dry matter produced	–	NLG m^{-2}
Y_f	rate of production (harvestable fresh weight)	–	$g\ m^{-2}\ h^{-1}$
α	conversion efficiency CH_2O to structural dry weight	0.7	$g\ g^{-1}$
β	angle of sun height	0.3	rad
Φ	rate of air exchange	–	$m^3\ m^{-3}\ h^{-1}$
ρC_p	volumetric heat capacity of air	1200	$J\ m^{-3}\ K^{-1}$

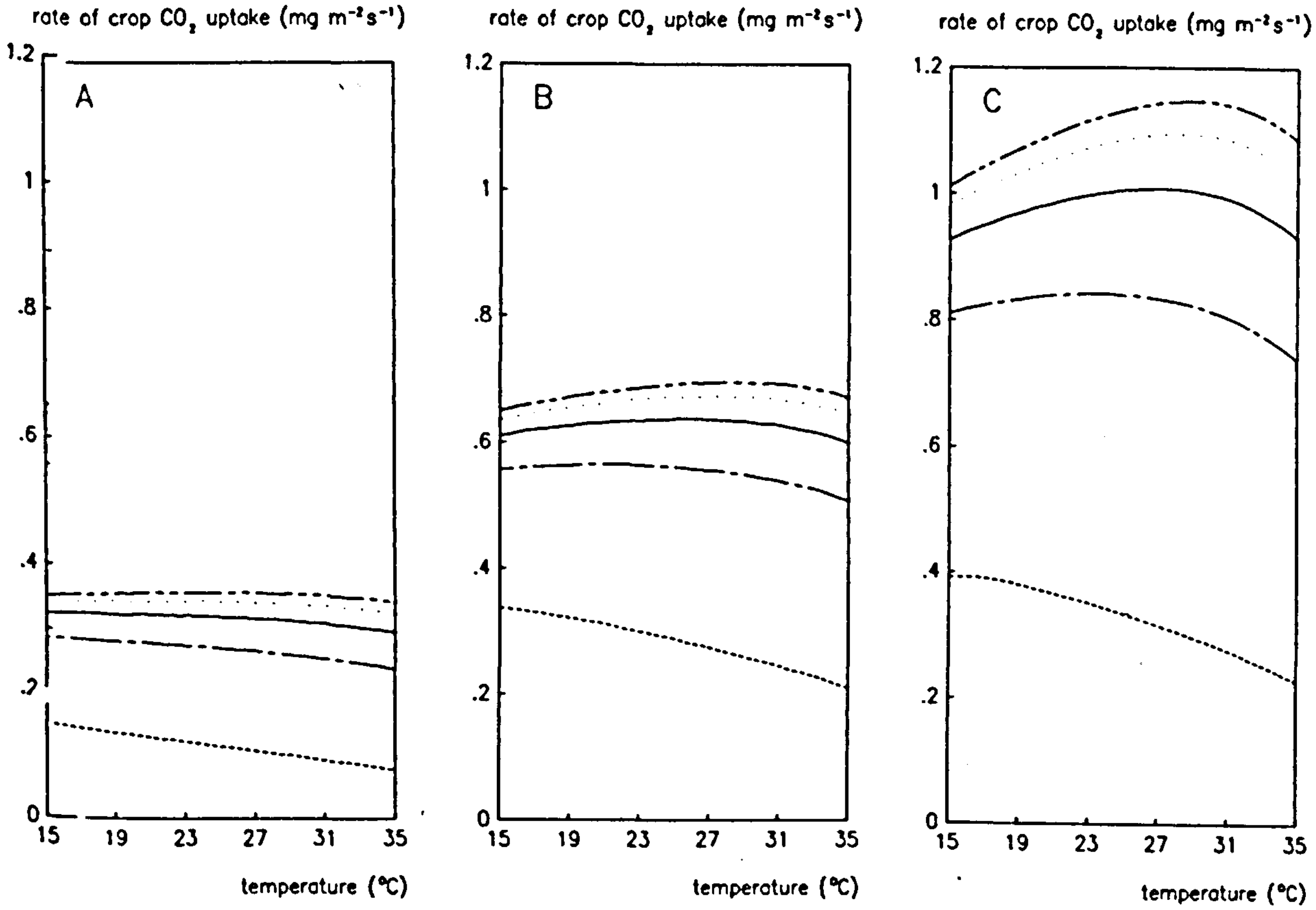


Figure 41. Simulated rate of gross photosynthesis of a crop as a function of temperature at photosynthetically active radiation of 25 W m^{-2} (A), 50 W m^{-2} (B) and 100 W m^{-2} (C). CO_2 pressures as in Figure 40. Leaf area index = 3. Other parameteres are given in Table 10.

$$C_s = A_c + \Phi\, h\, d\,(C_i - C_o)/P \qquad \text{Equation 21}$$

where
C_s = rate of CO_2 supply ($\mathrm{g\,m^{-2}\,h^{-1}}$)
A_c = rate of CO_2 assimilation by the crop ($\mathrm{g\,m^{-2}\,h^{-1}}$)
Φ = rate of air exchange ($\mathrm{h^{-1}}$)
h = average height of the greenhouse (m)
C_i = CO_2 pressure inside the greenhouse (Pa)
C_o = CO_2 pressure outside the greenhouse (Pa)
d = density of CO_2 ($\mathrm{g\,m^{-3}}$)
P = pressure of the air (Pa)

Energy consumption required to maintain the temperature difference between inside and outside was estimated very roughly using

$$Q = 3600\, e\, K\,(T_i - T_o) \qquad \text{Equation 22}$$

where
Q = energy consumption ($\mathrm{J\,m^{-2}\,h^{-1}}$)
e = efficiency of the heating system, including the boiler ($\mathrm{J\,J^{-1}}$)
K = factor (definition follows from Equation 22) ($\mathrm{J\,K^{-1}\,m^{-2}\,s^{-1}}$)
T_i = temperature inside the greenhouse (°C)
T_o = temperature outside the greenhouse (°C)

and where K is estimated, ignoring the latent heat loss, according to

$$K = K' + \Phi\, h\, \rho C_p/3600 \qquad \text{Equation 23}$$

where
K' = K factor without ventilation ($\mathrm{J\,K^{-1}\,m^{-2}\,s^{-1}}$)
Φ = rate of air exchange ($\mathrm{h^{-1}}$)
h = average height of the greenhouse (m)
ρC_p = volumetric heat capacity of air ($\mathrm{J\,m^{-3}\,K^{-1}}$)
For $h = 3$, Equation 23 reduces to $K = K' + \Phi$.

The cost of maintaining the desired level of CO_2 is obtained by multiplying the CO_2 supply by the price of CO_2. Likewise, the cost of maintaining the desired temperature is obtained by multiplying the fuel consumption required to cover the rate of energy consumption by the price of fuel. All parameters used for the calculations are presented in Table 10.

8.5 Response surfaces

The models and equations presented in the previous section enable response surfaces of *RNPPR* to be constructed as a function of the two inputs considered, air temperature and CO_2 pressure inside the greenhouse. These response surfaces only provide a static description; the dynamic aspects of the physical and physiological responses that, as pointed out previously, have to be taken into accont for control, are ignored. Two principally different situations are considered in the case of a cucumber crop:

1. 'Heat demand', with a heat demand and given air exchange rate.
2. 'Ventilation requirement', where ventilation is required in order to maintain the temperature set-point, and where the air exchange rate is a function of the temperature inside the greenhouse, the outside temperature and the global radiation.

When there is a ventilation requirement, the rate of ventilation Φ is calculated according to Equation 23 and the definition of K

$$\Phi = ((R_g/(T_i - T_o)) - K')\,3600/(h\,\rho C_p) \qquad \text{Equation 24}$$

where

Φ = rate of air exchange (h^{-1})

R_g = global radiation inside the greenhouse ($J\ m^{-2}\ s^{-1}$)

T_i = temperature inside the greenhouse (°C)

T_o = temperature outside the greenhouse (°C)

K' = K factor without ventilation ($J\ K^{-1}\ m^{-2}\ s^{-1}$)

h = average height of the greenhouse (m)

ρC_p = volumetric heat capacity of air ($J\ m^{-3} K^{-1}$)

For $h = 3$, Equation 24 reduces to $\Phi = (R_g/(T_i - T_o)) - K'$.

8.5.1 Situation 1, heat demand

When the greenhouse is heated the optimization problem is that energy and additional CO_2 are required to maintain a given temperature and CO_2 pressure (Figure 39). In the Netherlands, CO_2 is usually available for free when there is a heat demand, because exhaust gases from the central boiler are used as a source, and in that case only temperature control has to be optimized. Below the more complicated case where liquid CO_2 is used as a source is worked out, where a financial input is required for both temperature and CO_2 control.

The results of the calculations of *RNPPR* are presented in the form of contour plots because two factors are involved. The slope of the response curve is expressed by the density of the contour lines (Figures 42 and 43). Two situations have been considered, a low rate of ventilation of 1 $m^3\ m^{-3}\ h^{-1}$ (Figure 42A, C, E) and a high rate of ventilation of 10 $m^3\ m^{-3}\ h^{-1}$ (Figure 42B, D, F). At high radiation the optimum is very pronounced (Figure 42E, F) and the optimum conditions are little affected by ventilation, indicating that the effect on the cost of the inputs is small compared with the effect on the value produced. At lower radiation levels the effect of ventilation is much greater and there is a clear shift of the optimal conditions towards lower CO_2 concentrations and lower temperatures. Furthermore, there is an obvious interaction of CO_2 pressure and temperature: at low CO_2 pressure the optimum temperature is lower than at high CO_2 pressure. At 25 $W\ m^{-2}$ and high ventilation (Figure 42B) the optimum conditions

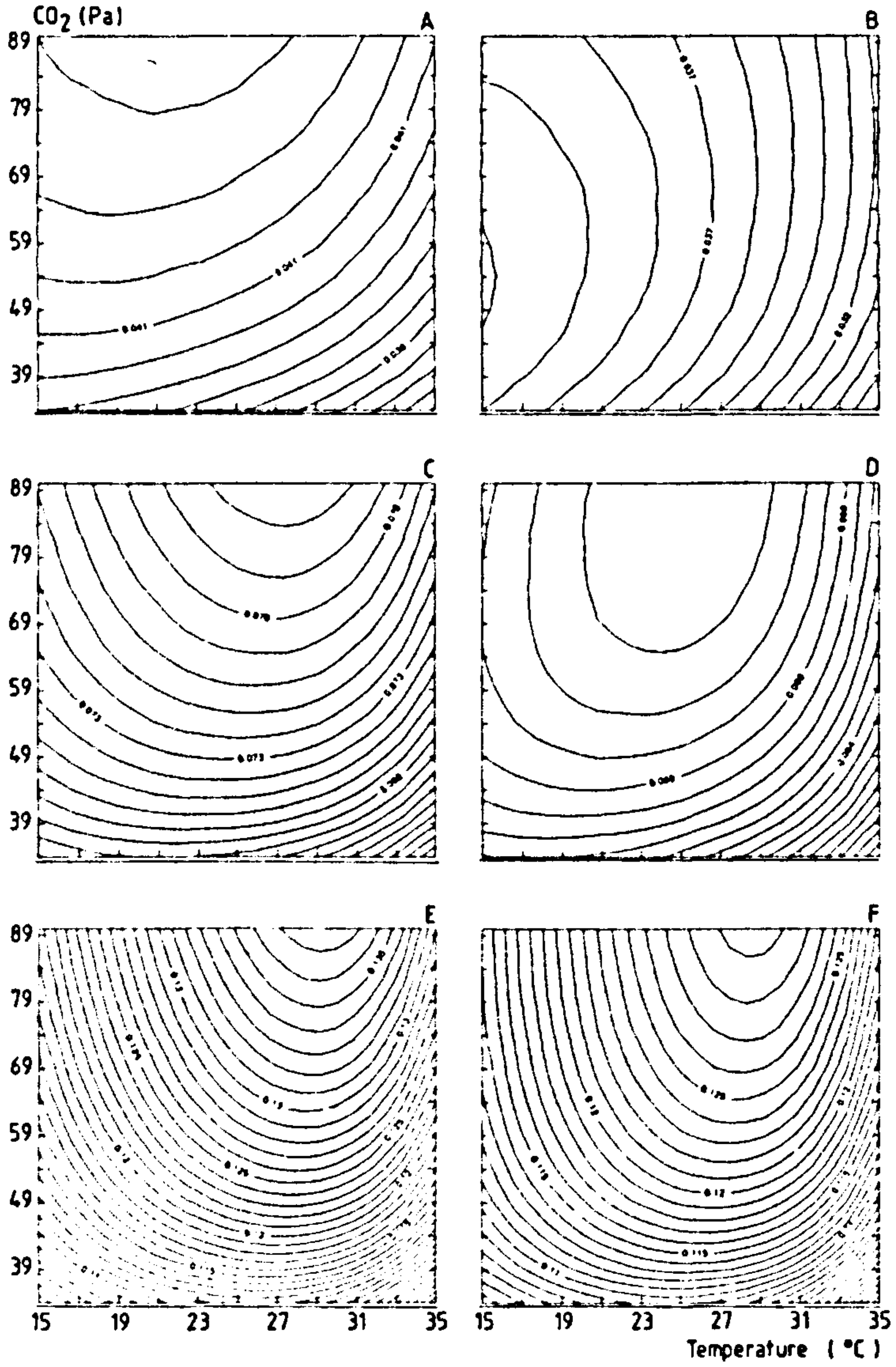


Figure 42. Relative net profit production rate (NLG m^{-2} h^{-1}) as a function of CO_2 pressure and temperature. Temperature controlled by heating. Photosynthetically active radiation inside the greenhouse of 25 W m^{-2} (A, B), 50 W m^{-2} (C, D) and 100 W m^{-2} (E, F). Fixed air exchange rate of 1 m^3 m^{-3} (A, C, E) or 10 m^3 m^{-3} (B, D, F). Price of CO_2 is 0.20 NLG kg^{-1}, price of gas is 0.20 NLG m^{-3}, price of cucumbers is 4.00 NLG kg^{-1}. Outside temperature is 10 °C.

shift to temperatures where the validity of the model is questionable: the model does not account for the strong decrease of photosynthesis at temperatures below ca. 17 °C, as has been pointed out previously.

The same situation was also investigated in the case of higher prices of CO_2 and fuel, a situation that is likely to occur in the Netherlands in the future (Figure 43) and that is probably more common in many other countries. The results obtained show a clear difference with Figure 42: the effect of ventilation on the response surface is much more pronounced, even at high irradiation. Furthermore, these examples clearly show the importance of dynamic optimization. Optimal climate conditions are indeed not only a matter of maximizing photosynthesis but may

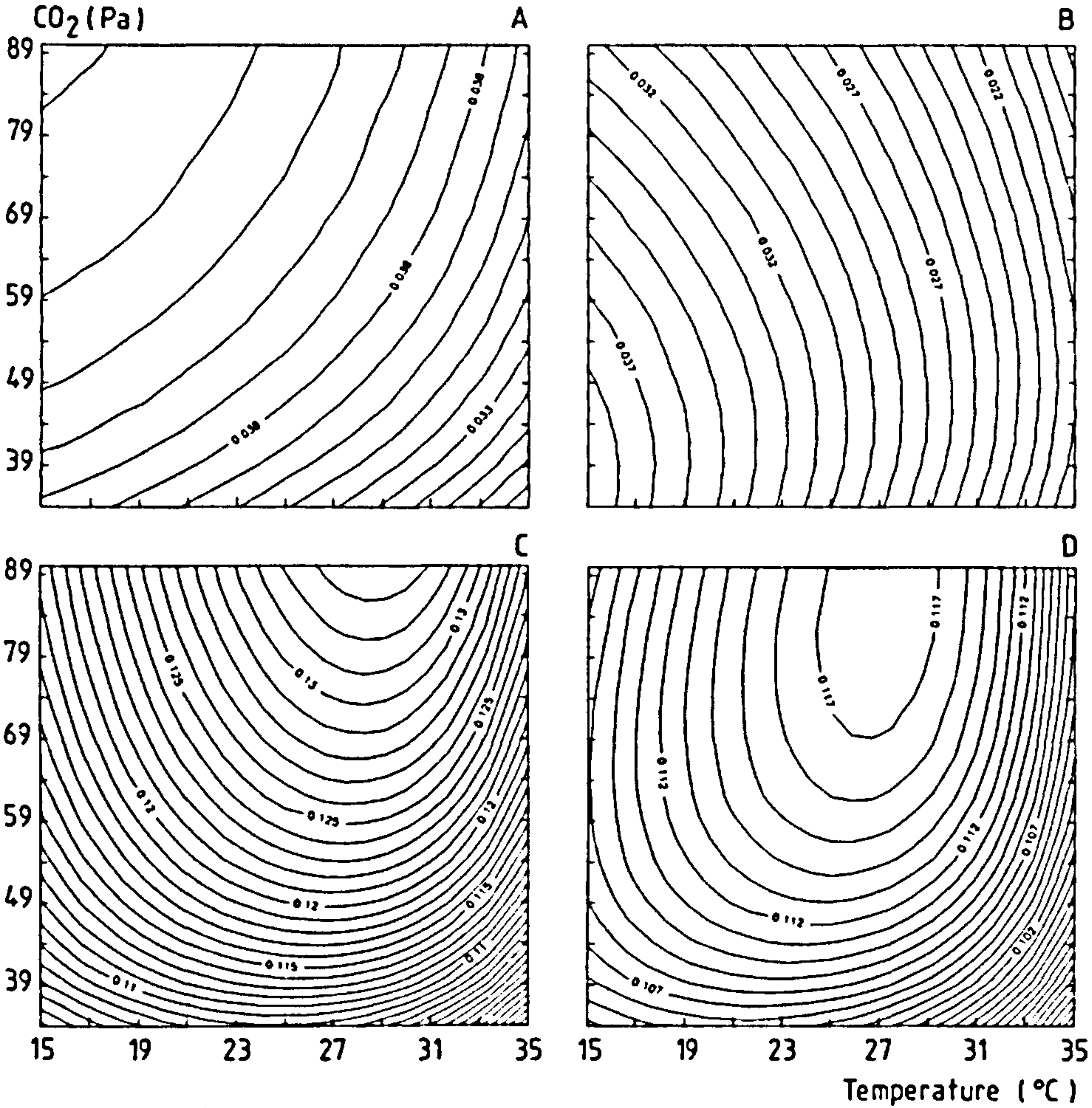


Figure 43. Relative net profit production rate (NLG m^{-2} h^{-1}) as a function of CO_2 pressure and temperature. Temperature controlled by heating. Photosynthetically active radiation inside the greenhouse of 25 W m^{-2} (A, B) and 100 W m^{-2} (C, D). Fixed air exchange rate of 1 m^3 m^{-3} (A, C) or 10 m^3 m^{-3} (B, D). Price of CO_2 is 0.40 NLG kg^{-1} and price of gas is 0.40 NLG m^{-3}. Other parameters as in Figure 42.

depend strongly on various economic factors, such as the price of the product, of fuel and of CO_2 (Compare Figure 42 with Figure 43).

8.5.2 Situation 2, ventilation requirement

When only ventilation is required to maintain a given temperature set-point, because there is a surplus of energy as a result of solar radiation, the main cost factor in this optimization problem is maintenance of the CO_2 pressure desired (Figure 44). In this case optimum temperature is high at both low and high radiation because the high ventilation rate that is required in order to maintain a low temperature leads to a high demand for CO_2. The range of temperatures is smaller than in Situation 1, because only ventilation control is considered and the maximum temperature that may occur depends on the energy supply by radiation.

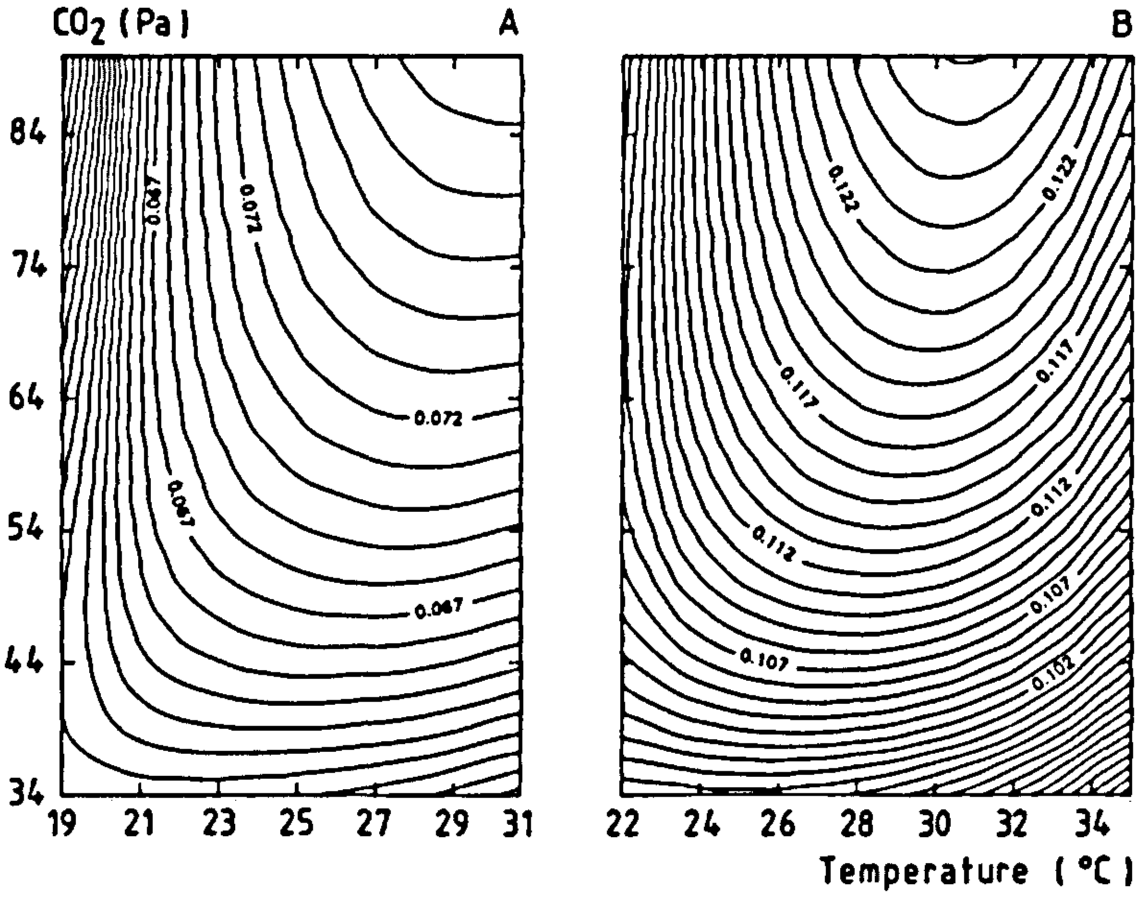


Figure 44. Relative net profit production rate (NLG $m^{-2} h^{-1}$) as a function of CO_2 pressure and temperature. Temperature controlled by ventilation. Photosynthetically active radiation inside the greenhouse of 50 W m^{-2} (A) and 100 W m^{-2} (B). Price of CO_2 is 0.20 NLG kg^{-1}, price of gas is 0.20 NLG m^{-3}, price of cucumbers is 4.00 NLG kg^{-1}. Outside temperature is 17 °C.

8.5.3 Conclusions

The simple examples that have been discussed make clear that dynamic optimization may be important because substantial benefit can be obtained. For an early planted cucumber crop in the Netherlands, the value produced during the first 83 days of the production cycle (the period where the price used in our calculations prevails) is in the order of NLG 29 per square metre of greenhouse floor (Anonymous, 1988). Assuming an average daylength of 10 h, the average value produced per hour is about NLG 0.035 m^{-2}. In Figures 42, 43 and 44 the iso-*RNPPR* lines differ by NLG 0.001 m^{-2}, or 3% of the average value produced. *RNPPR* differences of this order of magnitude are certainly relevant, because the extra cost for a system providing optimal climate control will be small. A better evaluation of optimized climate control requires extensive simulation runs using generated average weather conditions and a greenhouse model more elaborate than the simple version used here.

Optimal conditions depend on a great number of factors, which will change from moment to moment, from year to year, and from grower to grower. It is, however, important to notice here that the price of the product at the time of harvest is normally unknown at the moment the required assimilates are produced. Because this price depends strongly on the situation of the market it is impossible to obtain accurate predictions. As a result, accurate optimization is, in general, impossible, even if the crop models are very accurate.

In any case it is clear that in order to improve present greenhouse climate control systems, models that enable all relevant input and output factors to be evaluated in real time are required. The rapid development of powerful hardware will make it feasible to introduce models as a tool for optimizing greenhouse climate control. Horticulturists, engineers and plant physiologists are faced with the challenge of developing systems that are able to use the great potentials of modern greenhouse technology adequately.

8.6 The future

It has been pointed out already several times that, of course, maximization of the relative net profit production rate (*RNPPR*) is not the only objective of climate control. In general the following objectives can be formulated:

- high yield at reasonable cost
- optimal planning of production (labour requirement, market)
- product of good quality
- risk minimization
- maintenance of the production potential of the crop
- good labour conditions.

Maximization of *RNPPR* should thus be considered within the overall framework of the objectives mentioned. It will not be easy to integrate these objectives in future control systems, however. A proposal for an integrated system of short-term optimization and long-term planning of production was presented previously (Challa, 1985). In that set-up, requirements resulting from long-term decisions were linked to short-term optimization in terms of fixed limits for acceptable climatic conditions and average target conditions for humidity and temperature. The disadvantage of this one-way approach is that the knowledge that is available at the short-term level is not used to modify those limits. Thus, for example, if a minimum air humidity is formulated as a general rule for all conditions, it is obvious that refinements can be made if other instantaneous conditions that interfere in the problems caused by low humidity are also taken into account. Otherwise, the range of conditions that are defined as acceptable may be so small that little room is left for optimization.

In fact, more dynamic limits could be established if the relevant processes and their relations to the condition of the crop and the prevailing situation were understood. Unfortunately, this kind of knowledge is mainly present in the form of the grower's practical knowledge and therefore has a poor scientific basis and is badly documented.

A systematic survey of this 'grey' knowledge is urgently required and should be supplemented by a careful scientific analysis to enable it to be integrated with quantitative knowledge of physiological processes. Future climate control systems for greenhouse culture must rely on symbiosis of qualitative (knowledge systems) and quantitative models, in which the interaction with the grower is essential (Figure 45). The grower's knowledge that could be used is primarily qualitative and can be expressed in term of 'if... then' rules. Quantitative models

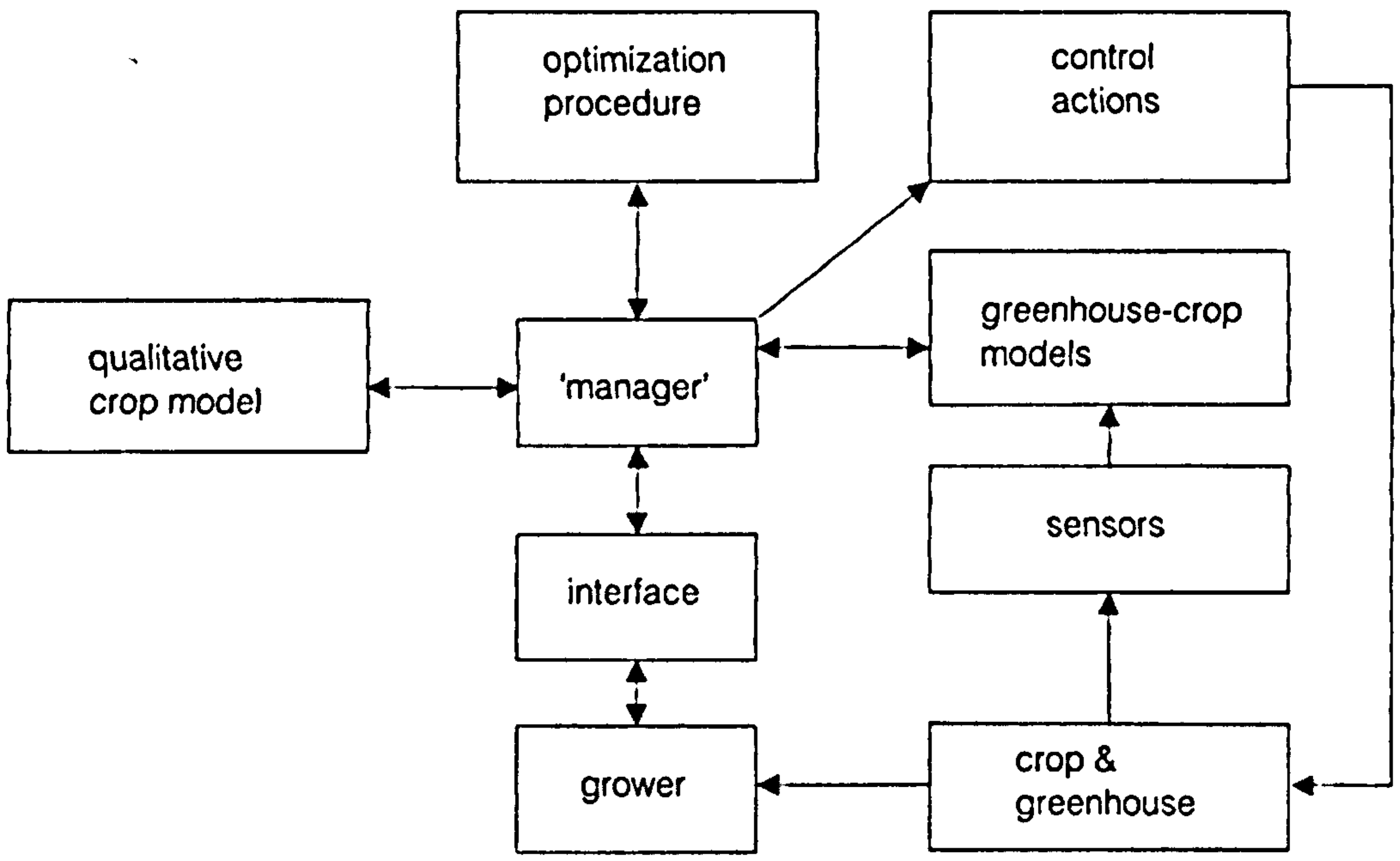


Figure 45. General architecture of future control systems.

support the qualitative model as one of the knowledge bases that can be consulted. In addition, the qualitative model will receive information from the grower who, by observations of the crop, possibly supported by a decision-support system, and given his general management policy, is able to manipulate the crop in the way desired.

Depending on the deviation from the 'ideal' situation, the qualitative model determines the room for optimization (Figure 46). Under 'normal' conditions a standard strategy is followed (blueprint), which is a sub-set of the conditions that could be generated by the optimizing control system. The room for optimization can be limited further if problems are expected. In that case the grower will switch to the 'prevent strategy', where priority is given to preventing the problems that might occur, rather than to optimization, if there is a conflict between these objectives. The smallest range of acceptable conditions is generated in the case of the 'recover strategy'. Of course the 'prevent' and 'recover' strategies are directly related to the problems that might or do occur, and are not general strategies.

Greenhouse climate control systems such as those described here are still wishful thinking. As stated before, knowledge required for their construction is still largely lacking. In addition, artificial intelligence is a new area and consequently obtaining proper and reliable tools is also a problem. Others (Jones et al., 1989; Schmidt-Paulsen, 1989) have also argued in favour of a combined approach that uses quantitative and qualitative models. This approach is probably essential, if models are to be used in agriculture.

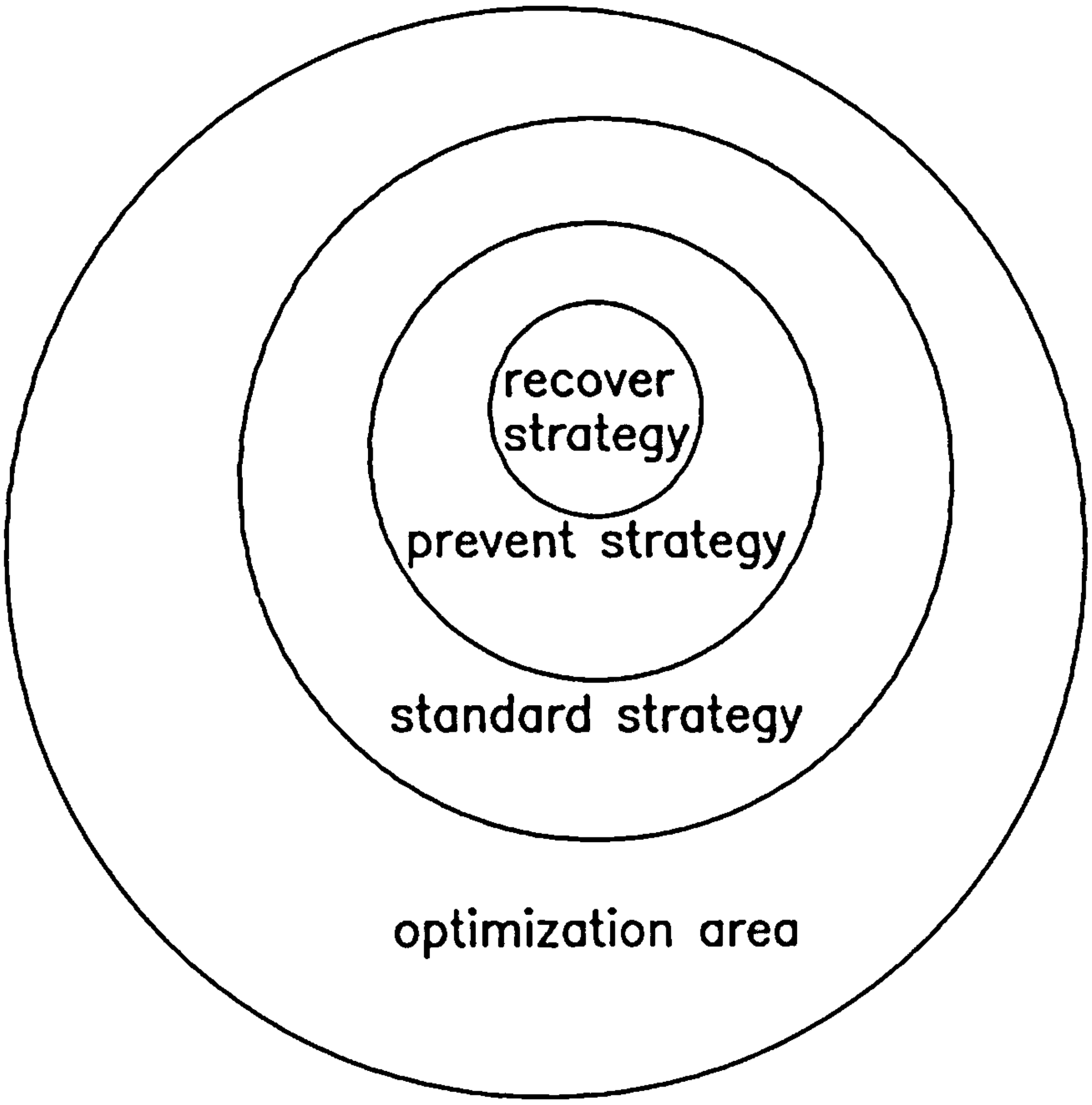


Figure 46. The optimization space and the limits set by 'standard', 'prevent' and 'recover' strategies.

8.7 Acknowledgments

The assistance of Dr G.P.A. Bot, Department of Agrotechnique and Physics, Wageningen Agricultural University, the Netherlands, in setting up a simplified procedure for the calculation of CO_2 and energy requirement is acknowledged. My thanks are also due to J.A. ten Cate, Centre for Agrobiological Research, Wageningen, who kindly provided me with a FORTRAN implementation of the routine for photosynthesis according to Farquhar et al. (1980).

Numerous discussions with Drs L. Maris, Department of Computer Sciences, Wageningen Agricultural University, and our students, T. van Dijk and P. Schotman, were of great value when developing the concepts mentioned in the section on the future.

I wish to thank my colleague Ir. E. Heuvelink for carefully reading the manuscript and making valuable comments.

8.8 References

Anonymous, 1987. Terminologie geautomatiseerde kasklimaatregeling. Stichting Mechanisatie Centrum, Wageningen, 31 pp.

Anonymous, 1988. Kwantitatieve informatie voor glastuinbouw. Proefstation voor Tuinbouw onder Glas, CAD groenteteelt, Naaldwijk & Proefstation voor de Bloemisterij in Nederland, CAD Bloemisterij, Aalsmeer.

Berry, J.A. & O. Björkman, 1980. Photosynthetic response and adaptation to temperature in higher plants. Annual Review of Plant Physiology 31: 491-543.

Berry, J.A. & J.K. Raison, 1981. Response of macrophytes to temperature. In: O.L. Lange, P.S. Nobel, C.B. Osmond & H. Ziegler (Eds): Physiological Plant Ecology I, Responses to the Physical Environment. Encyclopedia of Plant Physiology. New series. Volume 12A. Springer Verlag, Berlin, Heidelberg, Chapter 10, pp. 277-338.

Bot, G.P.A., 1983. Greenhouse climate: from physical processes to a dynamic model. Ph.D. thesis. Agricultural University, Wageningen, 240 pp.

Challa, H., 1985. Report of the working party 'Crop growth models'. Acta Horticulturae 174: 169-175.

Challa, H., 1988. Prediction of production, requisite of an integrated approach. Acta Horticulturae 229: 133-141.

Challa, H., 1989. Modelling for crop growth control. Acta Horticulturae 248: 209-216.

Challa, H. & A.H.C.M. Schapendonk, 1986. Dynamic optimalization of CO_2 concentration in relation to climate control in greenhouses. In: H.Z. Enoch & B.A. Kimball (Eds): Carbon dioxide enrichment of greenhouse crops. CRC press, Inc., U.S.A. pp. 147-160.

Challa, H., G.P.A. Bot, E.M. Nederhoff & N.J. van de Braak, 1988. Greenhouse climate control in the nineties. Acta Horticulturae 230: 459-470.

Farquhar G.D. & S. von Caemmerer, 1982. Modelling of photosynthetic response to environmental conditions. In: O.L. Lange, P.S. Nobel, C.B. Osmond & H. Ziegler (Eds): Physiological Plant Ecology II. Encyclopedia of Plant Physiology. New series. Volume 12B. Springer Verlag, Berlin, Heidelberg, pp. 549-582.

Farquhar, G.D., S. von Caemmerer & J.A. Berry, 1980. A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 species. Planta 149: 78-90.

Henten, E. van, 1989. Model based design of optimal multivariable climate control systems. Acta Horticulturae 248: 301-306.

Jones, P., B.L. Roy & J.W. Jones, 1989. Coupling expert systems and models for the real-time control of plant environments. Acta Horticulturae 248: 445-452.

Kozai, T. & S. Sase, 1978. A simulation of natural ventilation for a multi-span greenhouse. Acta Horticulturae 87: 39-49.

Penning de Vries, F.W.T., 1983. Modelling of growth and production. In: O.L. Lange, P.S. Nobel, C.B. Osmond & H. Ziegler (Eds): Physiological Plant Ecology IV. Encyclopedia of Plant Physiology. New series. Volume 12D. Springer Verlag, Berlin, Heidelberg, pp. 118-150.

Penning de Vries, F.W.T. & H.H. van Laar, 1982. Simulation of growth processes and the model BACROS. In: F.W.T. Penning de Vries & H.H. van Laar (Eds): Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen, pp. 114-135.

Schapendonk, A.H.C.M. & P. Brouwer, 1985. Environmental effects on photosynthesis, simulated and experimental results from a study on a 'tomato mini-crop'. Acta Horticulturae 174: 269-275.

Schmidt-Paulsen, T., 1989. Expert system technics as an extension of traditional modelling methods. Acta Horticulturae 248: 439-444.

Seginer, I., 1980. Optimizing greenhouse operation for best aerial environment. Acta Horticulturae 106: 169-174.

Spitters, C.J.T., H. van Keulen & D.W.G. van Kraalingen, 1989. A simple and universal crop growth simulator: SUCROS87. In: R. Rabbinge, S.A. Ward & H.H. van Laar (Eds): Simulation and systems management in crop protection. Simulation Monographs, Pudoc, Wageningen, pp. 147-181.

Strijbosch, Th. & J. van de Vooren, 1975. Developments in climate control. Acta Horticulturae 46: 21-22.

Udink ten Cate, A.J., 1980. Remarks on greenhouse climate control models. Acta Horticulturae 106: 43-48.