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Decision Support for Climate Dependent Greenhouse Production Planning and Climate Control by Modelling. II. Modelling Plant Growth

H. Krug, A. Romey and T. Rath
(Institute of Biological Production Systems, University Hannover, Germany)

Summary

On the basis of climate data and modules described in part I and the growth models of KRUG and LIEBIG (1994, 1995) and co-workers, the duration of defined growth phases of vegetable species and the respective energy demand for heating were parameterised as a function of sites (Helsinki, Hannover, Naples), season, energy saving installations (single and double glass, energy screen) and set points for heating. Special results are:

- the lower energy demand with higher set points as a result of accelerated growth of warmness demanding species or in warmness demanding phases at low external temperature
- at low air temperatures (set points) in greenhouses the accelerated emergence with lower energy demand with seeding in the ground soil compared to seeding into trays on tables
- the favourable effect of higher set points, when accelerated growth avoids unfavourable external conditions or reduces their growth retarding effects
- the absolute values of the energy saving effect of double glass (about 40 %) and of energy saving screens (7–35 %) per crop depend on species, climate and season
- the data calculated on the basis of the extended and improved submodels confirm earlier recommendations (KRUG and LIEBIG 1988, 1994, 1995) and extend them with regard to different sites, greenhouse types and sizes as well as energy saving installations. Their importance increases with cooler climates and/or seasons.

The calculations presented are examples, which can be specified and/or extended by other growth factors (e.g. CO_2, artificial light, soil heating) and other species. Other growth parameters and equations can be requested from the institute.

Key words. crop growth – energy demand – energy saving installations – greenhouse size and type – greenhouse climate – sites

Introduction

For well founded production planning and control in greenhouses in particular data on the external and internal environmental conditions, the reactions of the cultivated species, and the consequential energy demand are required. The first demand was outlined in part I. In part I, Fig. 7, accidentally a wrong caption has been printed. The correct caption should read: Fig. 7. Example for the correction factor to convert the heat demand based on Ltn (modelled by RATH 2007) to heat demand based on fluctuating climate datas (Reference year, BLÜMEL et al. 1986) for a single glass greenhouse at Hannover (100 m^2 ground area = —, 10000 m^2 ground area = ---) with 4 °C temperature set point reduction in the night. In this part the consequences for plant growth and respective energy demand for heating are modelled. The option is to check and extend the results and recommendations of earlier investigations on the basis of the more actualised submodels and to evaluate the impacts of a broader spectrum of climatic conditions and/or greenhouse design on crop growth and energy demand.

Material and Methods

The environment-plant-growth relationships are calculated on the basis of growth models at high abstraction level, summarised by KRUG and LIEBIG (1994, 1995) and KRUG (2002). These equations and parameters allow to estimate the duration of growth phases or of the total growth period as a function of season and intensities of uncontrolled and controlled growth factors (natural irradiance, artificial light, air and soil temperature, CO_2).

These equations are:

Emergence phase – all species tested (KRUG et al. 1985):

$$t_{(d)}=S*(T_{mean}-T_{min})^{-1} \quad (8)$$

$t_{(d)}$ = days, S = temperature sum (°C d, on daily basis KRUG 2002), T_{mean} = soil temperature or mean air temperature (° C) corresponding to soil temperature in trays on tables, T_{min} = basic temperature (°C).

Transplant phase – lettuce (KRUG and LIEBIG 1995):

$RGR_{(d)}=$
$A*[1-\exp(-c_1(x_1-x_{1min}))]*[1-\exp(-c_2(x_2-x_{2min}))]$
$*...[1-\exp(-c_n(x_n-x_{nmin}))]$ (9)

Accordingly AGR

RGR= Relative Growth Rate (g g^{-1} d^{-1}), AGR = Absolute Growth Rate (g d^{-1}), d = unit of time, A = maximal value of plant weight, x = growth factors (1 to n), c = coefficient for adaptation, x_{min} = factor intensity for growth = 0 (1 to n); exp(i)=e^i.

Plant growth (fresh weight) was simulated by an a) one-phase and b) a two-phases model :

$$a)\quad W(d) = Wo \cdot \exp\sum_{i=1}^{d} RGR(i) \qquad (10)$$

or alternatively

$$b)\ \text{phase 1: } W(d) = Wo \cdot \exp\sum_{i=1}^{d} RGR(i) \quad W(d) < 1\ g$$

and

phase 2 (let d' with W(d') ~ 1, for d>d'):

$$W(d) = 1 + \sum_{i>d'}^{d} AGR(i) \qquad (11)$$

W(d) = fresh weight (g) at day d, W_0= initial weight of the phase (1. phase 6.1 mg), RGR(i) = Relative Growth Rate at day i (–) accordingly AGR(i).

Duration is computed by the span between the day of beginning and the final day.

The *main growth phase – lettuce* was computed for 4 growth phases (2.5–10 g, >10–50 g, >50–100 g, >100 g) separately by the sum of the respective daily Relative Growth Rates:

$$W_{(\text{final weight phase x})}=W_0 * \exp\sum RGR_{(i)} \qquad (12)$$

(W_0 = initial weight of the respective phase).

The phase >100–150 g was calculated by an adjustment equation according to ALSCHER (1993). The multiple-phases-models, called "control models", are more flexible than the one-phase models (start to final value) and are presented in the respective figures. In these calculations, however, they resulted in pretty much the same values as the one-phase "planning models".

Concerning *cucumbers* the main growth phase was divided into the preharvest and harvest phase. The *preharvest phase* of cucumbers is defined as the period from planting (600 cm^2 leaf area) to 1 kg harvested fruits and calculated by an adjustment equation (by iteration) derived by RIPPEN and KRUG (1994, based on LIEBIG 1984):

$$t_{(d)}=156.3*e^{(-0.0475\ T)}*e^{(-0.0001885\ S)} \qquad (13)$$

$t_{(d)}$ = days, T = mean air temperature (°C), S = mean irradiance (Wh m^{-2} d^{-1}).

The *harvest phase* of *cucumbers* was defined as start of harvesting (1 kg fruits) to the last harvest (here Oct. 24th) and calculated according to RIPPEN (1993) in two steps: 1.) an equation to describe the seasonal trend of fruit yield and 2.) an equation to consider the actual growing conditions:

1.) $FB_{(w)}=a_0+a_1*\sin(2\Pi*cw*52^{-1})+a_2*\cos(2\Pi*cw*52^{-1})$

2.) $FR_{(w)}=FB_{(w)}+b_1*T+b_2*S+b_3*cw^{-1}+b_4*T^2+b_5*S^2+$
$b_6*T*S+b_7*T*cw^{-1}+b_8*S*cw^{-1}$ (14)

$FB_{(w)}$= basic yield per week, cw= calendar week, $FR_{(w)}$ = yield in fruits m^{-2} $week^{-1}$, T= mean temperature (°C) of the week, S= mean sum of irradiance per week (Wh m^{-2} d^{-1}), a= adjustment parameter for FB_w, b = adjustment parameter for $FR_{(w)}$.

Results and Discussion

Effects on plant growth and energy demand per crop

Emergence phase. The duration of the emergence period of the warm season crop *cucumber* and the cool season crop *lettuce* as well as the respective heating energy demands at the three sites, both calculated for seeding in trays on tables (air temperature) are calculated as a function of the set point for heating, for single and double glass and for an energy saving screen.

Concerning **cucumber** (Fig. 9a), emerging at March 1st , the *duration* of the emergence period drops drastically with higher set points and – due to equalizing temperature by heating – is about alike in Hannover and Helsinki. The energy saving installations do not show distinct effects. In Naples the trend is the same with a minor slope. Seeding in pots (air temperature) and in the soil does not result in remarkable differences.

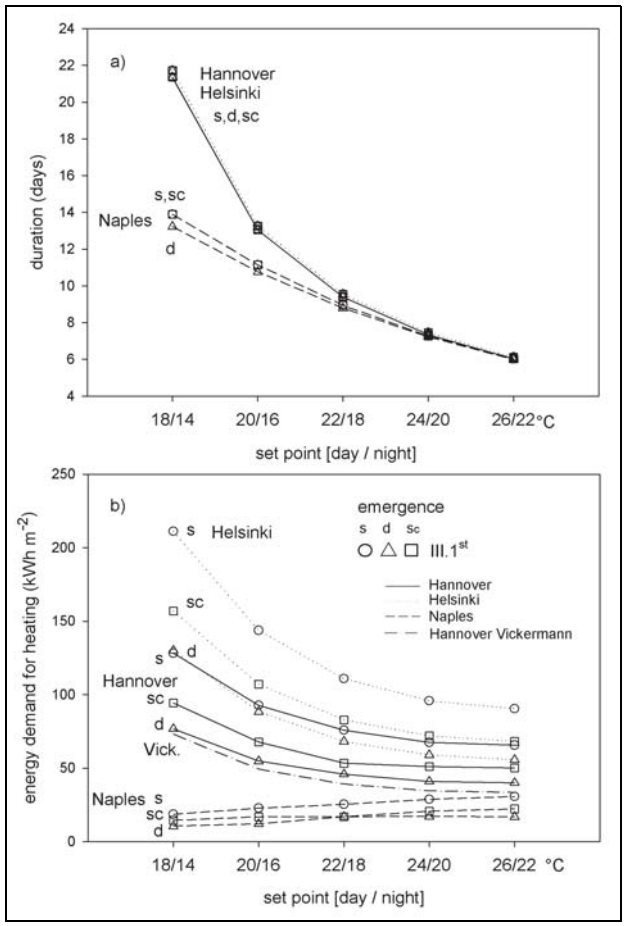


Fig. 9. a) Duration of the emergence phase (sowing–emergence) and b) respective energy demand of the warm season crop cucumber, emerging March 1st (reference point) in greenhouses (100 m^2) with different set points for heating and with and without energy saving installations at three sites with different climates (s =single glass, d= double glass, sc = energy screen), Vick. = calculation with the Vickermann-model (1969).

The *energy demand* for the emergence period (Fig. 9b) is low with a small increase with higher set points at the warm site Naples. At the cooler sites, however, the energy demand drops remarkably with higher set points up to about 24/20 °C and the more the cooler the site. That means, enhanced germination by higher temperature overcompensates the higher energy demand per day. The *energy saving installations* distinctly reduce energy demand, almost independently of the set points. Double glass saves about 40 %, the screen 26 % of the energy afforded for single glass; in approximation these values are valid for all sites.

Concerning **lettuce** the *duration* of the emergence period in the still warm autumn (emergence Oct. 1st) is about equal at all sites, independently of set point and energy saving installations (Fig. 10a). In winter time (emergence Feb. 1st) the same is true for Naples, whereas in Hannover and Helsinki a steep decline is obvious from 4/4 °C to 10/6 °C. The influence of energy saving installations on the emergence period is negligible.

The *energy demand* for the emergence period (Fig. 10b) is negligible in autumn at all sites, only with the highest set point, which will never be used in practice, some energy would be required. In winter time (emergence Feb. 1st) the energy is also negligible in Naples. In the cool sites the energy demand – like cucumbers – drops with higher set points, especially from 4/4 °C to 10/6 °C and in Helsinki distinctly more so than in Hannover. The *energy saving installations* reduce the energy demand in February at the cooler sites – that means with a noteworthy energy demand – in an average over all set points by 44 % (double glass) and 32 % (screen), respectively. The effect increases with cooler sites (Hannover 36 %, Helsinki 39 %) and cooler seasons.

Seeding directly into the soil of the greenhouses (2 cm depth) instead into trays with air temperature with emergence in February results in a remarkable reduction of the emergence period with the lowest set point (4/4 °C, corresponding to about 6 °C mean soil and 4 °C mean air temperature at both sites, Fig. 11a). The energy demand (Fig. 11b) was reduced by 38 % in Hannover and 48 % in Helsinki. With higher air temperatures (set point 10/6 °C with about 8 °C ; 14/10 °C = 11–12 °C) the differences in the duration become small and the energy demand increases a little with set points >10/6 °C (10–11 °C air and soil temperature) with soil seeding. With double glass the reductions were almost the same. These results confirm earlier calculations with parsley (Krug et al. 1985).

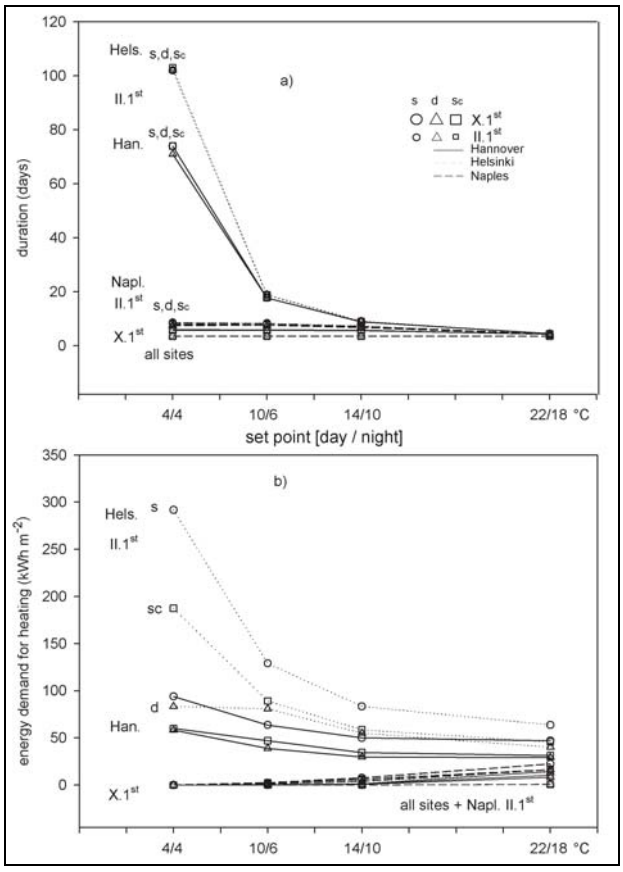


Fig. 10. a) Duration of the emergence phase (sowing–emergence) and b) respective energy demand of the cool season crop lettuce, emerged at October 1st and February 1st (reference points) in greenhouses (100 m²) with different set points for heating and with and without energy saving installations at three sites (symbols see Fig. 9).

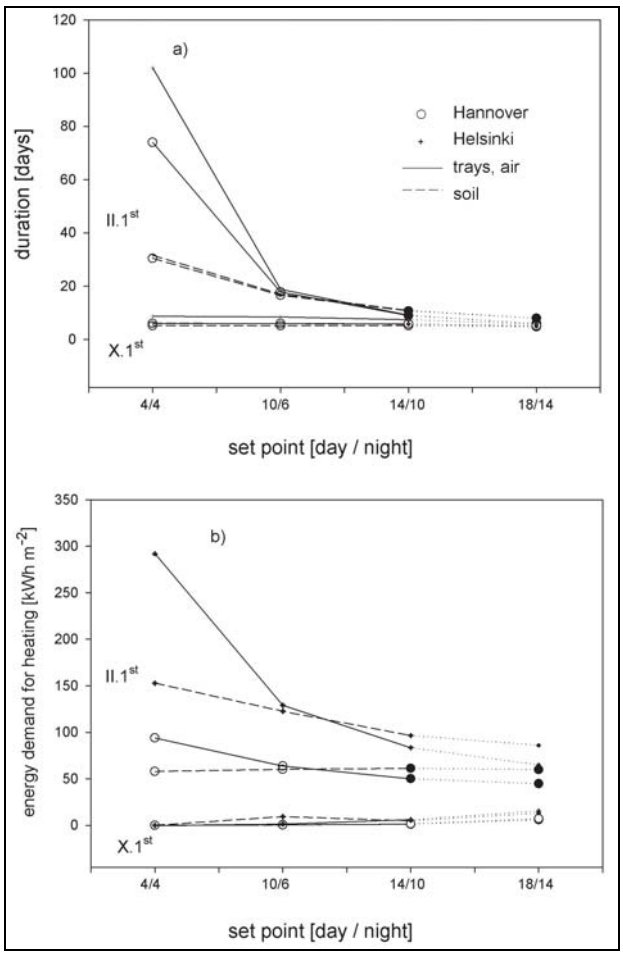


Fig. 11. Reduction of a) emergence phase and b) respective energy demand of lettuce by direct seeding into the soil (2 cm depth) compared to seeding into trays on tables with air temperature in single glass greenhouses at Hannover and Helsinki according to equation (5).

Transplant phase. For warm season crops unfortunately no feasible parameters are available. With the cool season crop lettuce increasing set points in warm climates have no, with cool sites only small shortening effects on the *duration* of the transplant phase at the dates of emergence calculated (Fig. 12a). In the warmer sites also the differences in duration between the emergence dates are small. *Double glass* has a somewhat prolonging effect in the darker season – due to reduction of irradiance. More pronounced are the effects on the *energy demand* for heating (Fig. 12b). In contrast with the emergence period it increases with higher set points, especially at cooler sites. *Double glass* reduces the energy demand in the cool spring season of Hannover by about 40–44 % when heated; somewhat less in Helsinki. With October plantings with low set points in Hannover double glass even increases the energy demand, probably by reduced irradiance, prolonging the growth phase.

Main growth phase. Concerning the *duration* of the main growth phase of **lettuce** (4–150 g, this harvest weight is below those used in practice, but it can be assumed that higher harvest weights will show the same trends and will increase the differences) the reaction to the set points is such as with transplants with somewhat more shortening with higher set points with the October planting in Helsinki (Fig. 13a). Concerning the *energy demand* (Fig. 13b) an interesting reaction becomes obvious: With the October planting in Helsinki and set points above 10/6 °C less energy is needed than with lower set points. This can be explained by faster growth in the autumn, shortening the growth period in the dark winter months. Due to quality reasons these temperature regime, however, can not be recommended for practice. *Double glass* reduces the energy demand in the range of 40 % with respect to the February planting and with about 25 % with the October planting. The lower value of the October planting is due to the prolonged growth period.

Concerning **cucumbers** the parameters of the *preharvest phase* (Rippen 1993) are derived from spring plantings and are not validated for other seasons. Another restriction is a small overestimation at temperatures below 18 °C due to using a linear regression model. This, however, is a temperature region, which in case of cucumber raising will occur only in exceptional cases. For these reasons the values for December and July plantings shown in Fig. 14 are not proved, but the trends can be considered close to reality.

The longer duration of the preharvest phase with the more northern sites is quantified and open to simulations. It drops with higher set points – except July planting at Naples (Fig. 14a). This occurs almost linearly, with a little bit steeper slopes at the more northern sites and in the less favourable seasons. *Double glass* prolongs the preharvest period on the average by 1.9 days in Naples, and with Naples highest outside temperatures somewhat more than in Hannover and Helsinki and in the warm July plantings more than in March. In December plantings this effect is negligible. Concerning the set points in this respect no significant effect is noticeable.

Accordingly the *energy demand* generally increases with higher latitudes, with less favourable seasons and with higher set points for heating (Fig. 14b). Remarkable

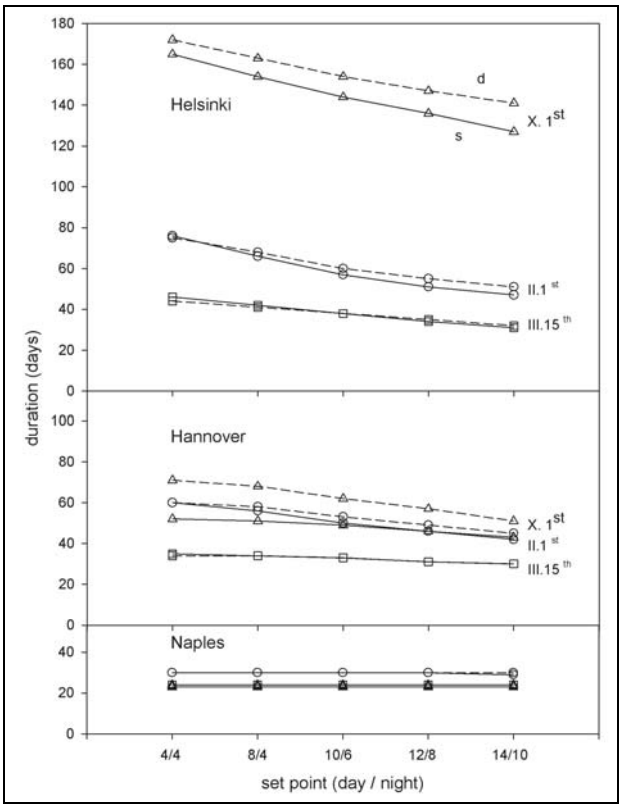


Fig. 12a. Duration of the transplant phase of lettuce in greenhouses (emergence – 4 g FW), single glass (—), double glass (---), X. 1st = day of emergence.

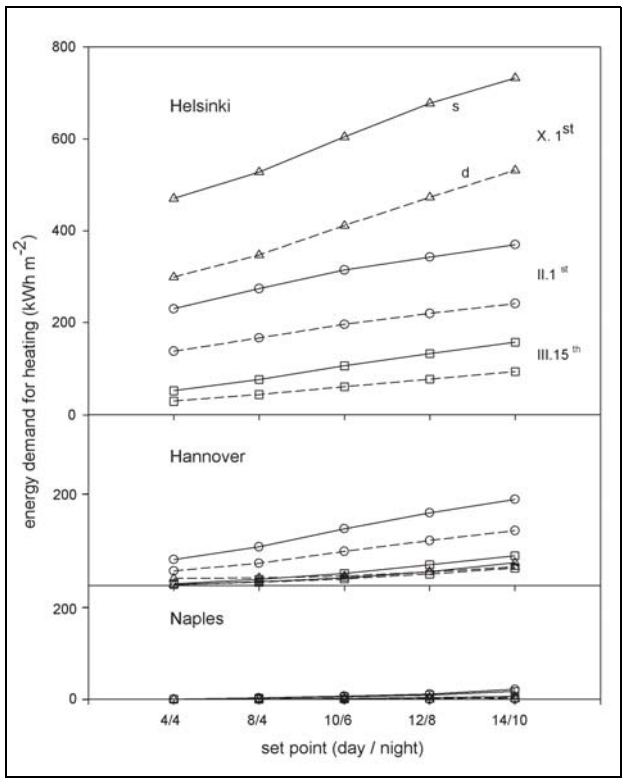


Fig. 12b. The respective energy demand as a function of set point for heating, site, planting date and double (---) compared to single glass (—), X. 1st = day of emergence.

is the trend to equal or even less energy demands with higher set points in more unfavourable climatic conditions, such as the December plantings in the northern sites. Here higher temperatures compensate for lower irradiances. Remarkable is also the lower energy demand for the July planting in Helsinki compared to Hannover, due also to higher irradiances. *Double glass s*aves energy for heating by about 38 % under all conditions checked.

The data of the *harvest phase* are measured from May to September/October with mean temperatures of 25 sets from 13.8 to 21.2 °C (RIPPEN 1993). Also in this phase yields were overestimated at mean temperatures below 18 °C. Due to this situation the calculations are restricted to the summer month and the values for Naples have to be interpreted with caution.

The fruit weight and the energy demand of cucumber as a function of site, set point and single and double glass greenhouses, respectively, in the period of May to August is presented in Fig. 15. At all sites the yields decline rather steadily with higher set points. The mean inside temperatures of the total harvest period deviate barely between Hannover and Helsinki and with 19–23 °C meet the optimal temperature range deduced for this phase (20–22 °C, KRUG et al. 1988). If the course of inside temperature is analysed in more detail, the initial inside mean day temperature in Helsinki with 14.5 °C is about 1.5 °C cooler than in Hannover, the same is true in the last weeks. This may contribute to the higher yields computed for Helsinki. In Naples, with a mean phase temperature of about 25 °C and mean day temperatures in August up to 28 °C, the optimum temperature is clearly exceeded. Therefore, even if the low temperature range may be somewhat overestimated, the preference of low set points is obvious.

This result agrees with earlier deductions in Hannover and is explained by an acceleration of fruit growth by high temperature on the cost of leaf/stem growth and fruit set (more particulars see KRUG et al. 1988). The high yields at Helsinki can be traced back primarily to the higher irradiances (Fig. 3 in part I), a dominant factor in this growth phase (KRUG et al. 1988). In Naples the effect of high irradiances will be compensated by the super optimal temperature. Double glass reduced the fruit yield appreciably, the energy demand is reduced in this period to about 56 %, more or less independently of set point.

General Discussion and Conclusions

As already outlined in part I modelling always comprises simplifications, all the more with increasing complexity of comprehensive systems. Concerning the growth models, the regression models used present statistical relationships between criteria of the complex system "environment" and the complex system "crop". The problems involved are discussed among others by KRUG and LIEBIG (1994, 1995). At the current state, however, the regression models resulted in more realistic estimates than the mechanistic models available in this field (e.g. ALSCHER 1993). Weaknesses in this investigation may be

- the not yet validated application of the parameters derived in Hannover to other sites, but in Helsinki and at least in the winter season of Naples the growth factor intensities do not exceed the ranges tested in Hannover

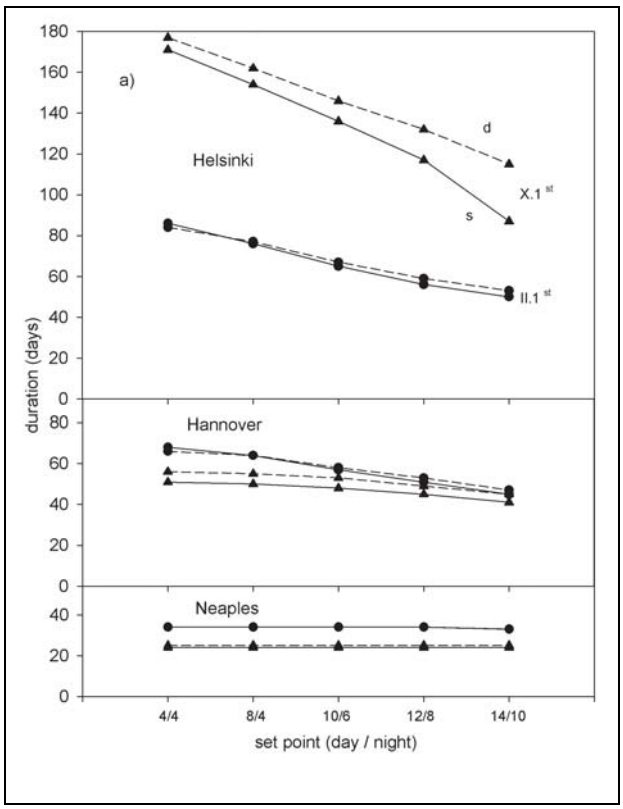


Fig. 13a. Duration of the main growth phase of lettuce in greenhouses (4–150 g FW, symbols see Fig. 12).

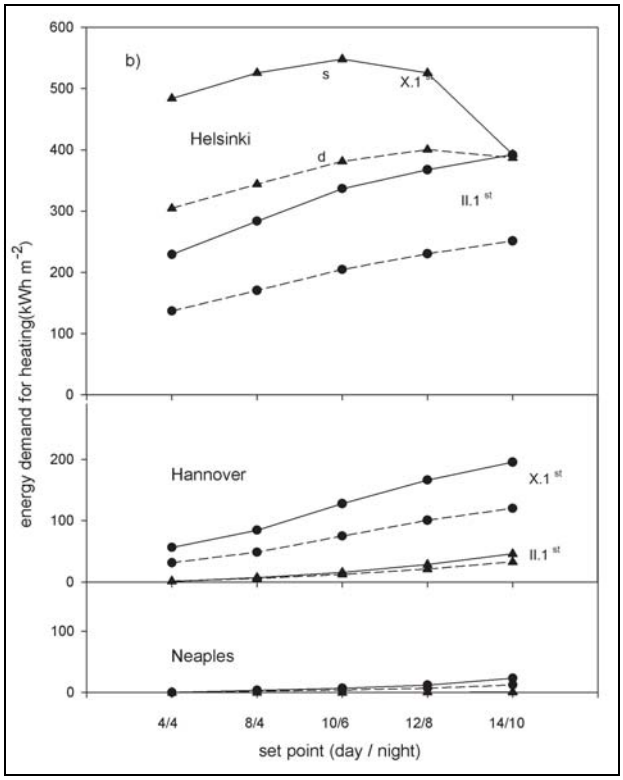


Fig. 13b. The respective energy demand as a function of set point for heating, site, planting date and double (---) compared to single glass (——), X. 1st = day of planting.

- the actions and interactions of/with other growth factors, not considered in these calculations, such as different CO_2-concentrations from enrichment to high concentrations to deficiency effects with tight greenhouses or higher air humidity with double glass
- the individual reactions of cultivars and their proveniences. In the experiments of RIPPEN (1993), however, the effects of cultivars remained in acceptable dimensions.
- different special basic conditions, such as soils, production techniques or phytopathological aspects

All these insufficiencies cause uncertainties, however, not all of them are system inherent and can be reduced at least partially by extended experiments and validations. Furthermore it has to be stressed that the data and coherences shown are decision supports only and can not precisely represent the particular system.

Beyond the well known relationships main results are:

- Acceleration of plant growth by higher set points for heating must not result in higher energy demands. It decreases, if a crop or phase with a strong temperature reaction (warm season crop, young plants) is grown at low outside temperature. This happens especially, when growth acceleration shortens growth under unfavourable conditions (Fig. 9, 10b, 11b, 13b, 14b).
- With low set points during cool periods direct seeding of cool season plant seeds into the warmer soil of the greenhouse resulted in a reduction of the emergence period and energy demand compared to seeding in trays on tables with air temperature (Fig. 11)
- Double glass reduces the energy demand by about 40 %, but this effect may be reduced, when the growth phase is prolonged by reduced irradiance (Fig. 12b, Hannover, October planting)
- The trends derived from the site Hannover hold in general for the sites of the other climates tested, when respective adjustments are considered.

The calculations with the more detailed and expanded submodels for greenhouse climate confirm the earlier deductions (KRUG et al. 1988, 2002). Concerning energy demand for heating the values of the Rath-model (RATH 1994) exceed those of the Vickermann-model (VICKERMANN 1969). The Vickermann values, however, approximate the Rath-model values for large greenhouses (Fig. 8 in part I). Therefore the recommendations derived from the earlier model calculations are confirmed and distinctly expanded.

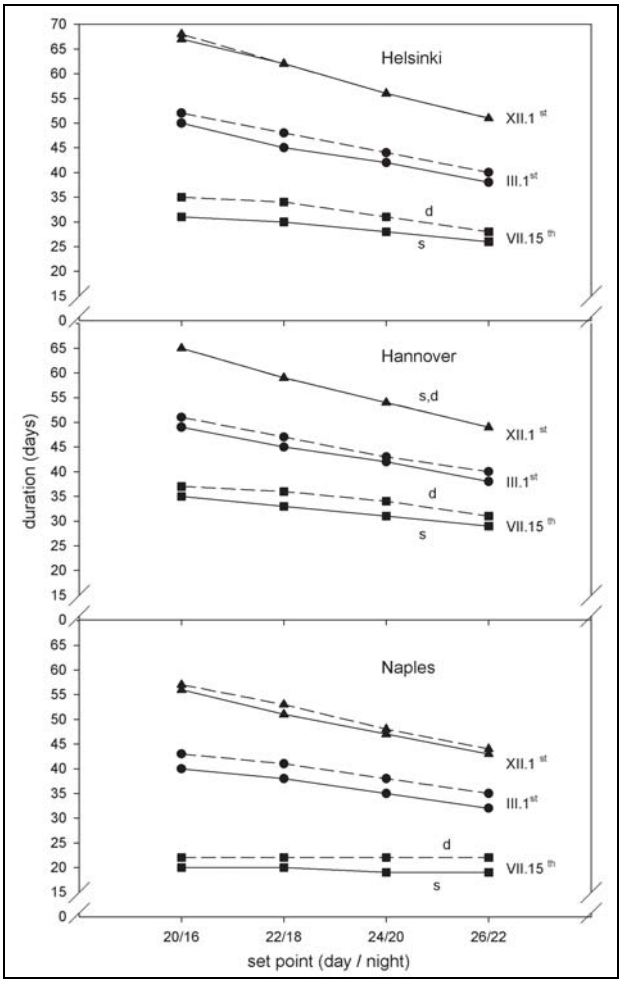


Fig. 14a. Duration of the preharvest phase of cucumbers [planting with 600 cm² leaf area to start of harvesting (1 kg fruits), symbols see Fig. 12].

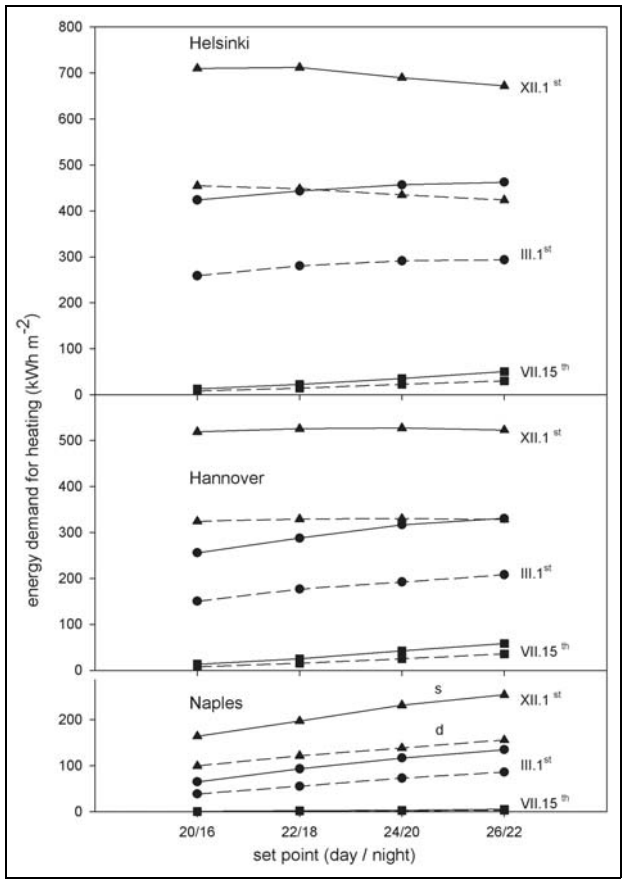


Fig. 14b. The respective energy demand as a function of the set point for heating, site, planting date and double (---) compared to single glass (——), XII. 1st = day of planting.

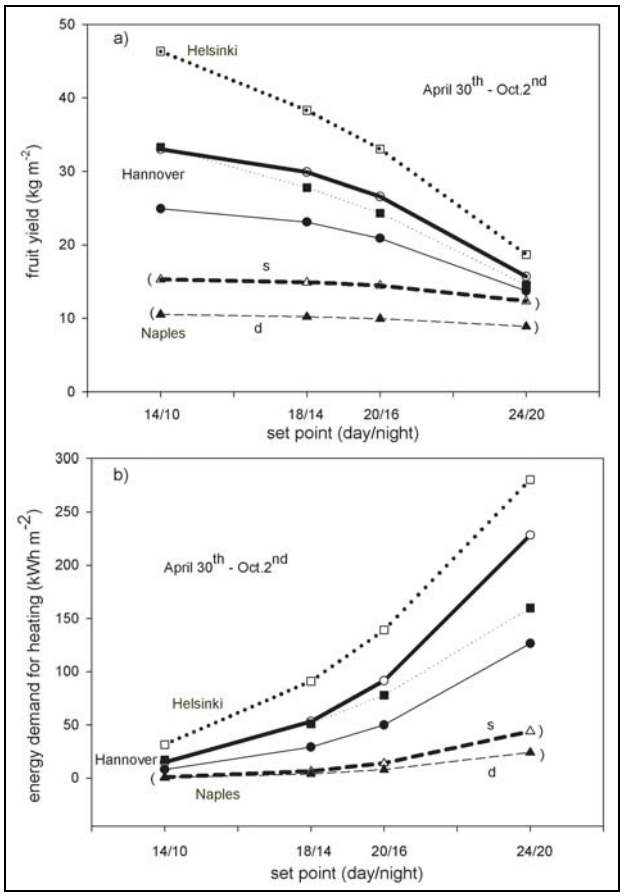


Fig. 15. a) Fruit weight (≥500 g) of cucumber cultivars in greenhouses in the period of April 30th to September 2nd and b) the respective energy demand for heating as a function of set point for heating, site, single (bold) and double (thin) glass.

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Addresses of authors: Helmut Krug (corresponding author) and Anni Romey, Institute of Biological Production Systems, Section Vegetable Systems Modelling, Leibniz University Hannover, 30419 Hannover, Herrenhäuserstr. 2, Germany, and Thomas Rath, Institute of Biological Production Systems, Section Biosystem- and Horticultural Engineering, Leibniz University Hannover, 30419 Hannover, Herrenhäuserstr. 2, Germany, e-mail krug@gem.uni-hannover.de.