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Optimisation of CO_2 and temperature control in greenhouse crops by means of growth models at different abstraction levels III. Simulation and optimisation with the combined model[1)]

Optimierung der CO_2- und Temperaturführung bei Gewächshauskulturen mit Hilfe von Modellansätzen unterschiedlicher Abstraktionsebenen III. Simulation und Optimierung mit dem kombinierten Modell

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Summary

To use the advantages of models at high and those of low abstraction levels for optimising greenhouse climate control, in part I a concept of combining a REGRESSION model with the physiologic-dynamic SUCROS 87 model has been developed and model parameters have been deduced from literature. In part II the parameters of the REGRESSION model based on growth phases and of the SUCROS model have been derived and validated.

In this III. contribution lettuce growth is simulated and optimised (see part I) using the REGRESSION model for growth phases (LETPHASE) and for daily growth (LETDAY) as well as the SUCROS model for simulating hourly growth rates (LETHOUR). Validation resulted in rather precise simulations of LETPHASE and LETDAY and overestimation by LETHOUR. Therefore at the end of each day LETHOUR was traced back to LETDAY, resulting in LETCOUPL. All models were traced back to real weight at the end of each week. An economic evaluation resulted in the highest gross margin (including opportunity costs) for LETCOUPL. The differences to LETPHASE and LETDAY, however, were small.

The weak points of the models are discussed. For final conclusions on the potentials of the models used and the advantage of coupling more experiments are needed.

Zusammenfassung

Um die Vorzüge von Modellen auf hoher und niedriger Abstraktionsebene für die Optimierung des Gewächshausklimas zu nutzen, wurden in Teil I ein Konzept für die Kombination eines REGRESSIONS-Modells mit dem physiologisch-dynamischen Modell SUCROS entwickelt und Modellparameter aus Literaturangaben abgeleitet. In Teil II wurden die Parameter des REGRESSIONS- und des SUCROS-Modells ermittelt und validiert. In diesem III. Beitrag wird das Wachstum von Kopfsalat mittels des REGRESSIONS-Modells für Phasen (LETPHASE) und für tägliche Wachstumsraten (LETDAY) sowie mittels des SUCROS-Modells für stündliche Wachstumsraten (LETHOUR) simuliert und optimiert. Die Validierung ergab recht präzise Simulationen für LETPHASE und LETDAY und eine Überschätzung des Wachstums durch LETHOUR. Deshalb wurde an dem Ende eines jeden Tages LETHOUR auf LETDAY zurückgeführt (LETCOUPL). Alle Modelle wurden nach jeder Woche dem realen Kopfgewicht angepaßt. Die ökonomische Auswertung ergab die höchsten Deckungsbeiträge (inklusive Flächennutzungskosten) für LETCOUPL. Die Differenzen zu LETPHASE und LETDAY waren jedoch gering.

Die Schwachpunkte der Modelle werden diskutiert. Für abschließende Schlußfolgerungen zu den Potentialen der verwendeten Modelle und die Vorteile einer Kopplung sind weitere Untersuchungen notwendig.

Introduction

To optimise climate control in greenhouses based on physiological and economic criteria and to spare resources a concept has been developed to use the advantages of models at different abstraction levels by combining the REGRESSION model of KRUG and LIEBIG (1988, 1994) for long term modelling with the SUCROS model of SPITTERS et al. (1989) for periods < 24 hours. In part I of this series (ALSCHER et al. 2001a) the concept has been developed and parameters of greenhouse production are derived. In part II (ALSCHER et al. 2001b) parameters of the REGRESSION growth model have been elaborated to simulate daily growth rates as well as parameters of the SUCROS model to simulate hourly growth rates. In this contribution the parameters and algorithms worked out are used to simulate daily and hourly growth of lettuce, respectively. Both models are combined according to the flow diagram outlined in part I, supposed to result in a more useful on-line control model for climate optimisation than each of the two approaches would achieve separately.

Simulation of lettuce growth

Prediction of Mean Growth Rates for growth phases (LETPHASE)

1) Based on the PhD-Thesis of ALSCHER (1993)

Table 1. Optimised set points for temperature (°C) and CO_2 concentration (μLL^{-1}) simulated for the four growth phases by means of LETPHASE and long term means of the climate. Bold numbers (*) indicate set points derived from the actualised climatic data.
Optimierte Reglereinstellungen für die Temperatur (°C) und die CO_2 Konzentration (μLL^{-1}), simuliert für die vier Wachstumsphasen mittels LETPHASE und langjährigen Mitteln des Klimas. Fette Zahlen (*) bezeichnen Reglereinstellungen nach aktualisierten Klimadaten.

Start of optimisation	phase 1		phase 2		phase 3		phase 4	
	CO_2	Temp	CO_2	Temp	CO_2	Temp	CO_2	Temp
Set 1								
Phase 1	**380**	**6/2***	400	6/2	400	6/2	380	6/2
Phase 2			**400**	**2/2***	380	6/2	380	6/2
Phase 3					**400**	**6/2***	380	6/2
Phase 4							**380**	**2/2***
Set 2								
Phase 1	**380**	**6/2***	380	8/2	400	6/2	380	6/2
Phase 2			**380**	**2/2***	400	6/2	400	6/2
Phase 3					**700**	**8/2***	380	10/2
Phase 4							**380**	**2/2***

To obtain a survey on suitable planting dates and set points for lettuce crop cultivation and for optimising temperature and CO_2 control, gross margin was calculated for nine planting dates using the PLANNING model of KRUG and LIEBIG (1994) and long term normals of climatic means (details see ALSCHER 1993). Plantings at 18.1. and 11.2. were selected.

Temperature and CO_2 control is based on constant set points for each of the four phases, optimised at the start of the respective crop, using the REGRESSION model and long term climatic means. Optimisation is realized by simulating daily Relative Growth Rates on the basis of the respective response surface parameters within each phase for a range of suitable set points. Selecting is performed according to the highest gross margin, which includes opportunity costs. When the ends of the respective phases were reached by simulation or by measured fresh weight of samples, actualisation is carried out by replacing the predicted climatic data by measured ones as well as simulated growth by measured fresh weight and resimulation. The required factor demands within the phases are calculated on the basis of respective data of the climate outside and the real temperature and CO_2 concentration inside the greenhouses. Based on real fresh weight and factor demand, optimisation of the climate for the remaining growth phases is repeated. This procedure is finished when harvest weight is reached.

Table 1 shows the simulated and actualised optimal climate regimes of the four growth phases. It is obvious that all set points are rather low and there is only a small range for optimisation. Consequently the differences between predicted set points and realised ones after actualisation are small, except set 2 phase 3 and 4, which show considerable changes between the phases concerning the set point for temperature and phase 3 for CO_2 concentration.

Table 2 presents the predicted and after actualisation realised periods of the four growth phases. The duration of the phases actualised was about 31, maximal 5 days shorter than predicted. This will be caused predominantly by deviating weather conditions from the long term means.

Table 2. Comparison of the duration of the phases and the total growing period, resulting from optimised set points at the beginning of each phase with long term climatic means and after actualisation of the climatic data using LETPHASE.
Phasen- und Kulturdauer nach zu Beginn jeder Phase mittels langjähriger Klimamittel optimierten Reglereinstellungen im Vergleich zur Optimierung mit aktualisierten Klimadaten mittels Modell LETPHASE.

Phase	phase period	
	simulated	actualised
set 1		
1	35	30
2	19	14
3	9	6
4	8	6
1—4	58	56
set 2		
1	24	20
2	15	12
3	6	5
4	6	4
1–4	43	41

Prediction of daily growth rates (LETDAY)

Daily growth rates are simulated by Relative Growth Rates within the four phases, estimated at the start of each day by means of the REGRSSION model and weather conditions derived from the foregoing day and optimised for this day and the remaining gowth period. At the end of the day an actualisation is carried out using the measured climatic data. Further feedbacks are the weekly measured weights of the lettuce plants.

Results are presented in figures 1 and 2. In fig. 1 the outside temperature, the set points for the optimised day temperatures and CO_2 concentrations of set 1 are plotted over the predicted irradiances to ascertain any correlation between set points and outside climate conditions. The graph shows relative constant values and no correlations between irradiance, outside temperature and the set points of temperature and CO_2, but some deviations are obvious. These cannot be explained physiologically, but may have been caused – at least partly – by wind velocity. The same pattern is true for set 2, but in the advanced season outside temperature increases more distinctly with irradiance.

In fig. 2 the demands of energy and CO_2 of set 1 are shown as a function of the actualised fresh weight. The en-

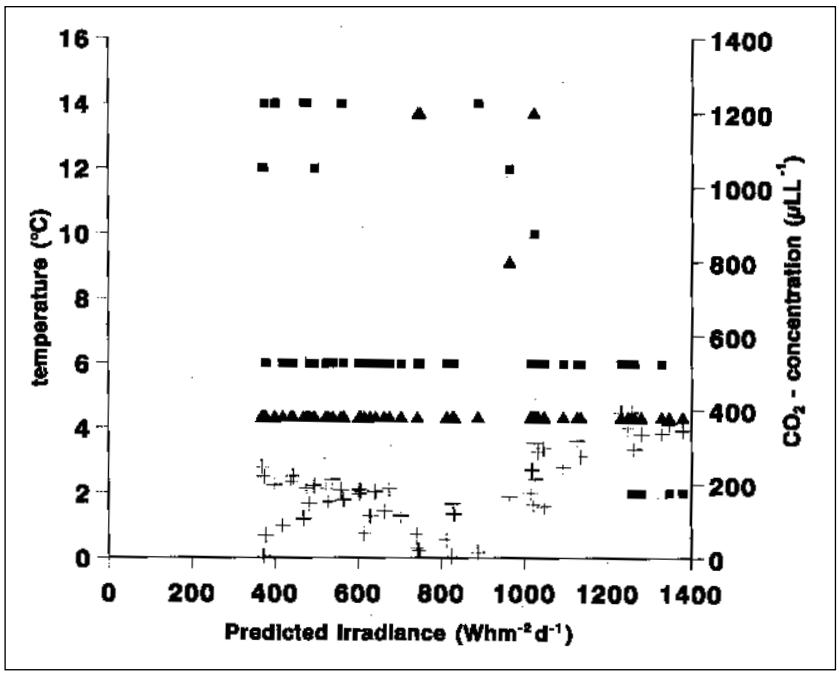


Fig. 1. Set points of day temperature (■, at night 2 °C) and CO_2 concentration (▲) optimised by model LETDAY, related to outside temperature (+) and predicted irradiances (set 1).
Reglereinstellungen der Temperatur (■, Nachttemperatur 2 °C) und CO_2 Konzentration (▲), optimiert mit LETDAY, in Beziehung zur Außentemperatur (+) und der geschätzten Bestrahlungsstärke (Satz 1).

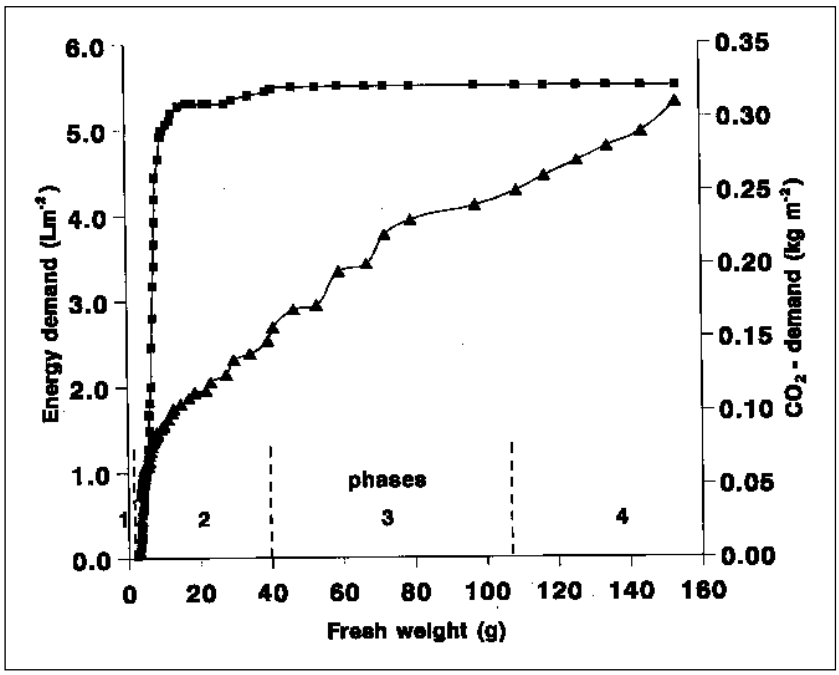


Fig. 2. Demands of heating energy (■) and CO_2 (▲) of set 1 as a function of actualised fresh weight, calculated by LETDAY.
Bedarf an Heizungsenergie (■) und CO_2 (▲) von Satz 1 als Funktion des aktualisierten Frischgewichtes, berechnet nach LETDAY.

ergy demand is high during the first phase with low outside temperatures and high temperature demand for leaf expansion. In the phases 3 to 4 almost no energy is used, due to more favourable outside climatic conditions and expanded leaves requiring lower temperatures for dry matter production. Concerning CO_2 concentration, higher daily quantities are simulated during phase 1 and 2, but considerable enrichment occurred also during the following phases as well. For set 2 the same pattern was found, but according to the more favourable seasonal conditions at a lower level.

Prediction of hourly growth rates (LETHOUR)

Hourly growth was simulated by the SUCROS model adapted to the lettuce crop (see part II) and weather data predicted. At the end of each hour the weather data are actualised and growth is resimulated. The factor demands were also calculated per hour and accordingly set points were optimised.

Fig. 3 demonstrates hourly CO_2 concentrations of a bright and a cloudy day, optimised by LETHOUR. High irradiances at noon lead to higher CO_2 concentrations and consequently to growth acceleration, saving energy and opportunity costs for greenhouse area. With low irradiances no enrichment beyond the minimum concentration of 380 μLL^{-1} occurred.

Comparison of the results gained by the

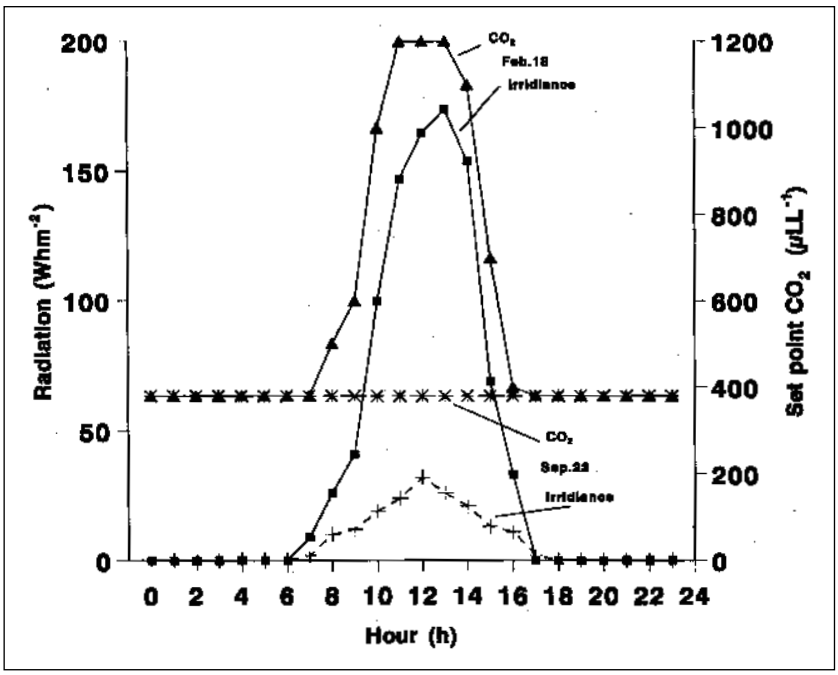


Fig.3. Set points of CO_2 concentration, optimised by LETHOUR for a bright day [Febr. 18., 91] and a cloudy day [Sept. 23., 91], in relation to irradiance [Febr. 18., 91, Sept. 23., 91] at an optimised temperature of constant 2/2 °C.
Reglereinstellungen für die CO_2 Konzentration, optimiert mit LETHOUR für einen hellen [18.2.91] und einen trüben Tag [23.9.91] in Beziehung zur Bestrahlungsstärke [18.2.91, 23.9.91] bei einer optimierten Temperatur von konstant 2/2 ° C.

different models

Growth periods

To validate the models and their parameters derived from the experiments from 1982/3 to 1988/9 (see part II, table 1), in 1991 a further experiment was performed, controlling one greenhouse by model LETPHASE, one greenhouse by LETDAY and a third greenhouse by LETCOUPL. Each greenhouse was divided into four replications.

To check variability of the four replications the growth curves of all replications of the three greenhouses were calculated with the FELDMANN function (FELDMANN 1979) and interpolated to 150 g fresh weight. The derived growth periods deviated between the replications only by one day, except set 1 of LETCOUPL by two days. This means a small variability.

To test the stability of the models the growth periods (150 g fresh weight) were derived by simulating growth by:

1. the PLANNING model (KRUG and LIEBIG 1994), using one regression function for the total growth period and MGR (Mean Growth Rate) and same climate regime for the whole cultivation period;
2. the regression model LETPHASE, using different regression functions for the 4 growth stages and RGR and the same climate regime for the whole stage;
   the regression model LETDAY using different regression functions for the 4 growth stages RGR and a different climate regime for each day of the cultivation period;
3. the model LETHOUR basing on physiological processes and compared to the experimental data. The means of measured climate data for the growing periods were presented as well.

The results are listened in table 3. With the PLANNING model the growing period was distinctly overestimated by 5 to 7 days (8–15%). LETPHASE overestimated the growing period by 3 to 5 days in set 1 (5–9%), but hit the target rather precisely in set 2. LETHOUR underestimated the growth period by 5 to 6 days in set 1 (10–12%) and 1 to 3 days in set two (2–6%).

Economic criteria

Based on the experiment with two sets in 1991 the cultivation period and economic criteria were simulated and optimised by means of the models LETPLAN, LETPHASE, LETHOUR and LETCOUPL (table 4). As has been expected the **cultivation period** decreases distinctly with the advanced season (set 2) and with optimisation in shorter periods. The differences between the models are relatively small except LETPLAN. The overestimation with LETPHASE has to be referred to deviating weather conditions to the long term means. The **monetary output** is equal, due to the same amount harvested and unchanged prices. Only LETPLAN with a remarkable longer growing period and lower product prices result in a somewhat lower monetary output.

Concerning factor demand **CO_2 consumption** is distinctly higher in LETCOUPL compared to the other models, especially in the first set. This is due to a higher rating of the CO_2 effect (part II, fig. 9) and hence higher CO_2 concentration. Comparing LETPHASE and LETDAY the differences in CO_2 demand are diverse in the two sets. The same is true for ranking LETPLAN with an increasing demand in the second set.

Concerning **energy demand** the dropping from the first to the second set runs parallel with all models despite of different reaction curves of the two approaches (part II, fig. 9). It is highest with LETDAY and lowest with LETCOUPL. The low energy demand of LETCOUPL may be a consequence of the response surface, reaching its maximum already at 5 °C.

The **opportunity costs** increase to set 2, due to higher productivity with the advanced season. The differences between the models – except LETPLAN – are rather small. LETCOUPL shows the lowest opportunity costs with the shortest growing period.

Regarding **gross margin** including the opportunity costs, the values of the three models – except LETPLAN – increase parallel from the first to the second set with the highest values of LETCOUPL. Those of LETPHASE are

Table 3. Validation of the different models by means of experimental data (150 g harvest weight) based on measured daily climate (experiment 1991).
Validierung der Modellansätze anhand experimentell ermittelter Daten (Erntegewicht von 150 g) auf der Basis gemessener täglicher Klimawerte (Versuch 1991).

Growth derived by	Climate control by LET-	climatic conditions (means) set 1 radiation ($Whm^{-2}d^{-1}$)	set 1 temp. (°C)	set 1 CO_2 (μLL^{-1})	set 2 radiation	set 2 temp.	set 2 CO_2	cultivation period days set 1	cultivation period days set 2	difference (model – experiment) set 1	difference (model – experiment) set 2
measuring and	phase	832	8,7	476	1106	12,0	475	55	40	–	–
Feldmann	day	812	8,8	464	1105	12,5	405	54	40	–	–
function	hour	812	8,4	583	1112	12,4	510	53	39	–	–
simulation											
LETPLAN	phase	895	9,4	473	1275	12,7	401	60	46	+5	+6
	day	895	9,6	461	1275	12,3	445	60	45	+6	+5
	hour	895	9,3	568	1265	12,6	495	60	46	+7	+7
LETPHASE	phase	870	9,1	476	1120	12,1	482	58	41	+3	+1
	day	870	9,2	463	1106	12,5	405	58	40	+4	0
	hour	870	8,9	576	1106	12,4	511	58	40	+5	+1
LETHOUR	phase	774	8,0	478	1114	12,0	466	49	38	–6	–2
	day	774	8,2	467	1112	12,6	405	49	39	–5	–1
	hour	772	7,7	599	1136	12,3	516	48	36	–5	–3

Table 4. Comparison of simulated cultivation period and economic results of the experiment 1991 (harvest weight 150 g).
Vergleich der simulierten Kulturdauer und ökonomischer Ergebnisse des Versuches 1991 (Erntegewicht 150 g).

Climate control by	set	cultivation period (d)	monetary output ($DM\ m^{-2}$)	factor demand CO_2 ($kg\ m^{-2}$)	factor demand energy ($L\ m^{-2}$)	opportunity costs ($DM\ m^{-2}$)	gross margin ($DM\ m^{-2}$)
LETPLAN	1	74	9,44	0,22	3,13	2,71	2,09
LETPHASE	1	58	9,76	0,38	4,70	1,62	2,58
LETDAY	1	55	9,76	0,31	5,51	1,43	2,43
LETCOUPL	1	54	9,76	0,62	3,78	1,36	3,11
LETPLAN	2	56	9,12	0,52	3,19	3,10	1,11
LETPHASE	2	41	9,60	0,37	1,66	2,08	3,49
LETDAY	2	41	9,60	0,44	2,01	2,08	3,26
LETCOUPL	2	39	9,60	0,50	1,29	1,95	3,7

somewhat higher than those of LETDAY. The very low value of LETPLAN in the second set is a consequence of high opportunity costs and high energy costs based on the rather long cultivation period predicted.

Discussion

The parameters of the growth models derived (part II) allow for simulation of growth as a function of the environmental conditions in the range investigated. Using the REGRESSION model it has to be decided which period will result in the best adaptation to reality. This refers to the ability of the plant to integrate varying inputs and the actualisation of input data, especially the weather data. If the weather data are comparable, the PLANNING model (KRUG and LIEBIG 1994), integrating the total growth period and the after-effects, is rather stable for predicting long periods. It is not suitable for considering ontogenetic effects and for short term weather actualisation.

Model LETPHASE reduces these restrictions, enabling to consider medium term ontogenetic reactions, such as germination (emergence phase), growth of leaves, flower initiation and others. Because of the restricted changes in the development pattern within the range investigated formal defined growth phases are preferred according to BAZLEN (1985). Considering the factors ontogenesis and actualisation of the weather data, it results in optimised set points, which are interpretable (table 1). This is reflected, for example, in low temperatures in phase 4. But there are variations as well, which cannot be interpreted at this time. For the cold season, however, the scope of variation is small for the species lettuce, leaving a small range for causal variation. Actualisation of the weather data on the contrary results in distinct differences, at least during the first phase. Summing up the corrections for the total growth period the differences become small.

Concerning LETDAY, generally the same reaction pattern is evident, a relative constancy and unexplained deflections. This approach, however, has the advantage of quickly weather actualisation and hence a more flexible on-

line control. The dynamics of the factor demands are interpretable (fig. 3). Their levels, however, contain uncertainties due to the incomplete demand models (heating energy see RATH 1992).

SUCROS, simulating growth potentials, overestimates real growth distinctly. In further experiments it has to be tested, if adaptation to real growth can be achieved by correction of internal parameters. More experiments have to be carried out to improve the response surfaces of primary growth components, especially for leaf growth and dry matter partitioning. Also after-effects, as shown to be important for photosynthesis by WIEBE und LORENZ (1982), need more investigation in physiological models.

Validation with the experiment of 1991 shows that in an average of the climate control models LETPHASE overestimates the growth period in set 1 by 4 days and in set 2 by less than 1 day (table 3). LETHOUR underestimates the growth period in set 1 by about 5 days, in set 2 by 2 days. Even if validation is performed only with two sets in one year, using identical greenhouses and measuring devices, a coupling of LETHOUR to LETDAY seems to be justified.

Comparing the gross margin (table 4), LETCOUPLE ranks first. This can be related to the higher CO_2 application with high irradiances, a factor which seems underestimated by the parameters of the REGRESSION model derived in this investigation. The differences to LETPHASE and LETDAY, however, are small. Therefore the growth models have to be improved and completed by including all main growth factors, such as water potential and nutrients. Furthermore quality of the lettuce heads and the risk of pest and disease attack should be considered, a field where modelling is still in a very preliminary stage. Moreover, more precision has also be achieved for the models calculating factor demands.

With reproduced or improved models the benefits to extend the REGRESSION model by a physiological dynamic model, such as SUCROS 87, should be checked. As costs for installing on-line control in computer controlled greenhouses are low, the risk of installing this additional modul is not high.

Literature

ALSCHER, G. 1993: Optimierung der CO_2- und Temperaturregelung bei Gewächshauskulturen mit Hilfe von Modellansätzen unterschiedlicher Abstraktionsebenen. Dissertation, Universität Hannover.

ALSCHER, G., H. KRUG und H.-P LIEBIG 2001a: Optimisation of CO_2- and temperature control in greenhouse crops. I. Control strategies, growth models and input data. Gartenbauwissenschaft 66(3), 105-114.

ALSCHER, G., H. KRUG und H.-P. LIEBIG 2001b: Optimisation of CO_2- and temperature control in greenhouse crops. II. Control strategies, growth models and input data. Gartenbauwissenschaft 66(4), 153-163.

BAZLEN, E. 1985: Modelluntersuchungen zu altersabhängigen Klimareaktionen als Basis für die Simulation des Wachstums am Beispiel von Radies (*Raphanus sativus var. sativus)*. Dissertation, Universität Hannover.

FELDMANN, U. 1979: Wachstumskinetik. Mathematische Modelle und Methoden zur Analyse altersabhängiger populationskinetischer Prozesse. Mediz. Informatik und Statistik 11, Springer Verlag, Berlin, Heidelberg, New York, 22.

KRUG, H. und H.-P. LIEBIG 1988: Planungsmodell für die Jungpflanzenanzucht. Gartenbauwissenschaft **53**, 241-247.

Krug, H. und H.-P. Liebig 1994: Model for planning and control of transplant production in climate controlled greenhouses. I. Production planning. Gartenbauwissenschaft **59**, 108-115.

RATH, TH. 1992: Einsatz wissensbasierter Systeme zur Modellierung und Darstellung von gartenbautechnischem Fachwissen am Beispiel des hybriden Expertensystems Hortex. PhD-Thesis, Univ. Hannover.

SPITTERS, C.J.T., H. VAN KEULEN and D.W.G. VAN KRAALINGEN 1989: A simple and universal crop growth simulator: SUCROS87. In: RABBINGE, R.; S.A. WARD and H.H. VAN LAAR, 1989: Simulation and system management in crop protection. Simulation Monographs, Pudoc Wageningen, 147-181.

WIEBE, H.-J. and H.-P. LORENZ 1982: Temperaturführung bei Kopfsalat im Gewächshaus. Auswirkungen auf Photosynthese und Wachstum. Deutscher Gartenbau **4**, 146-148.

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