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# Modelling Production Subsystems at High Abstraction Level – Reviewing Summary. II. Crop Parameters

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**Summary**

Based on general premises and considerations of models at high abstraction level, outlined in part I, this paper presents the parameters worked out for main vegetable species.

**Key words.** growth functions – growth phases – planning models – control models – growth efficiency.

## Introduction

Basic considerations, techniques and limitations of modelling at high abstraction level are outlined in part I of this paper (Krug 2008). In this part the parameters of autotrophic growth elaborated for different vegetable species are compiled.

## Crop parameters

*Definitions and abbreviations (see page 142)*

Radish (*Raphanus sativus* L. var. *sativus*) (Table 2 and Table 3).

Table 2. Radish (*Raphanus sativus* L. var. *sativus*), phase emergence → harvest

| Reference | Cultivar weight ($FW_{tuber}$) | Season/ sowing | Parameter/ ( ) = function | A | $c_1$(Ta) | $c_2$($S_i$) | $c_3$(C) | Min values | Ranges Ta Si C |
|---|---|---|---|---|---|---|---|---|---|
| [a)]K. & L. 1979 | 'Hilmar' em→4 g ≅200 mg DW | Oct.–Mar. | MGR (mg $d^{-1}$ DW) MLR (3) | | | | | | 5–18 300–1200 uc |
| [b)]M. 1986, 1987 | 'Hilmar' em→4 g | Sep.–Feb. | MGR (mg $d^{-1}$ DW) MR (4) | | | | | 2 70 100 | 3–18 170–2400 300–1200 |
| [c)]R. 1993; R. & K. 1994 | 5 cvs. em→4 g ≅200 mg DW | Oct.–Apr. | MGR (mg $d^{-1}$ DW) MR (4) | 11,870 | −0,27199 | −0,00081 | | 2 70 | 3–13 200–2100 uc |

[a)]Krug and Liebig 1979: The first basic publication; MLR: $MGR_{(em\rightarrow 200\ mg\ DW)}$ = 0,553+0,377 Ta+0,00168 Si−0,0353 Z−0,0133 $Ta^2$+0,00168 $Si^2$+0,000483 $Z^2$+0,000112 Ta∗Si−0,000573 Ti∗Z−0,0000239 Si∗Z. Including quality characters. The autumn sets showed stronger reactions.
[b)]Mann 1986, 1987: Aiming at the effect and economy of $CO_2$ enrichment. Parameters not retained, $CO_2$-elevation did not show significant reactions.
[c)]Rippen 1993; Rippen and Krug 1994: Experiments in 27 holdings at 4 sites, 60 sets, no significant season effects.

Table 3. Radish (*Raphanus sativus* L. var. *niger*)

| Reference | Cultivar weight ($FW_{tuber}$) | Season/ sowing | Parameter/ ( ) = function | A | $c_1$(Ta) | $c_2$($S_i$) | $c_3$(C) | Min values | Ranges Ta Si C |
|---|---|---|---|---|---|---|---|---|---|
| [a)]M. 1986, 1987 | 'Rex' planting (tuber 10 cm long→80 g) | Sep.–Oct. | MGR ($g\ d^{-1}$ FW) | 7,071 | −0,00058 | −0,50040 | −0,00863 | 2<br>70 | 3–18<br>170–2400 |
| | | Jan.–Feb. | MR (4) | 2,571 | −0,00168 | −0,25570 | −0,00835 | 100 | 300–1200 |
| [b)]K. & L. 1984a | 'Rex' em→100 g ≅ 3,13 g DW | Sep.–Apr. | MGR ($mg\ d^{-1}$ DW) MLR (3) | | | | | | 5–20<br>300–2400<br>uc |

[a)]Mann 1986, 1987: Aiming at the effect and economy of $CO_2$ enrichment.
[b)]Krug and Liebig 1984a: MLR: MGR = $a+c_1\ Ta+c_2Si+c_3C+c_4Ta^2+c_5Si^2+c_6C^2+c_7Ta*Si+c_8Si*C+c_9Ta*C$. Parameters not retained, results in diagrams only; including quality characters.

Lettuce (*Lactuca sativa* L. var. *capitata*) (Table 4 and Table 5).

Table 4. Lettuce (*Lactuca sativa* L. var. *capitata*): Transplant phase

| Reference | Cultivar/ weight (g FW) | Season sowing/ planting | Parameter/ ( ) = function | A | $c_1$(Ta) | $c_2$($S_i$) | $c_3$(C) | Min values | Ranges Ta Si C |
|---|---|---|---|---|---|---|---|---|---|
| [a)]K. & L. 1988 | 'Ravel' em→3 g FW | Oct.–May | MGR ($g\ d^{-1}$) MR (4) | | | | | 0<br>70<br>– | 5–14<br>280–2800<br>350 |
| [b)]K. & L. 1994 | 'Ravel' em (6,1 mg) →4 g FW | Oct.–Mar. | MGR ($g\ d^{-1}$) MR (4) | 0,220 | −0,16940 | −0,00156 | −0,00650 | 0<br>70<br>0 | 10–20<br>250–1600<br>350–970 |
| [c)]K. & L. 1995 | 'Ravel' em (6,1 mg) →1 g | Oct.–Mar. | RGR ($g\ g^{-1}\ d^{-1}$ FW) MR (4) | 0,393 | −0,13668 | −0,00183 | −0,00658[1)] | | |
| | 1,1→4 g | | ($g\ d^{-1}$ FW) | 0,588 | −0,26719 | −0,00131 | −0,00594[2)] | | |

[a)]Krug and Liebig 1988: The type of growth function is examined (exponential or logistic); significant season effect, eliminated by a season term (Weber and Liebig 1981): MGR = $A*(1-\exp c_1\ (Ta-Tmin) * (1-\exp c_2\ (S-Smin)+a+b \sin x+c \sin 2x+d \cos x+f \cos 2x$. ($x = 2\Pi*PM*365^{-1}$). Parameters not retained, diagonal diagram for LTN in Hannover and 27 single years; scaling of emerging dates for equidistant planting dates, energy demand.
[b)]Krug and Liebig 1994: Planning model: Including artificial light (0–20 $Wm^{-2}$ or 100 µmol $m^{-2}\ h^{-1}$ (PAR) for 10 h, factor 1,8 for global irradiance) and soil temperature (12–21 °C, $Ts_{min}$ 0 °C, coeff.−0,128751). Diagonal presentations. Effect of transplant weight and quality, factor cost.
[c)]Krug and Liebig 1995: Control model: To be continued by: [1)]coeff.: Sk=1,66, Ts= −0,16378; [2)]Sk=2,04, Ts = −0,096028. Growth simulation by equations 7, 8 or 9. Simulations show the effects of season and weather conditions of the year as well as by case studies the potentials to hit a fixed date.

Table 5. Lettuce (*Lactuca sativa* L. var. *capitata*): Planting to harvest phase

| Reference | Cultivar/ weight (g FW) | Season sowing/ planting | Parameter/ ( ) = function | A | $c_1$(Ta) | $c_2$($S_i$) | $c_3$(C) | Min values | Ranges Ta Si C |
|---|---|---|---|---|---|---|---|---|---|
| [a)]M. 1986, 1987 | 'Apollo' res | Sep.–Mar. | MGR ($g\ d^{-1}$ FW) MR (4) | 9,990 | −0,03947 | −0,00406 | −0,00873 | 2 | 3–18 |
| | 'Ravel' | Sep.–Mar. + st | | 4,611 | −0,15540 | −0,00271 | −0,00851 | 70 | 170–2400 |
| | 3→100 g FW | Sep.–Oct. | | 5,136 | −0,14200 | −0,00300 | −0,00765 | 100 | 300–1200 |
| | | Jan.–Mar. | | 4,193 | −0,13480 | −0,00296 | −0,01026 | | |
| [b)]R. 1993; R. & K. 1994; R. et al. 1994 | 7 cvs. 2,5→200 g FW | Sep–April | MGR ($g\ d^{-1}$ FW) MR (4) | 7,046 | −0,12553 | −0,00270 | | 2 70 | 2–14 250–2200 uc |
| [c)]A. 1993; A. et al. 2001a, b, c | 'Ravel' | Sep.–Feb. | RGR ($g\ g^{-1}\ d^{-1}$ FW) | 2,753 | −0,00880 | −0,00167[1)] | | 0 | 2–18 |
| | 2,5→10 g FW | | | | | | | 0 | 250–3000 |
| | >10→50 gFW | | MR (4) | 0,277 | −0,05847 | −0,00256 | | 0 | (300–1000) |
| | >50→100 g FW | | ($g\ d^{-1}$ FW) | 0,168 | −0,07600 | −0,00236 | | | |
| | >100→150 g FW | | GR [see[f)]] ($g\ d^{-1}$ FW) | 0,110 | −0,09896 | −0,00001 | | | calculated with 350 |

[a)]Mann 1986, 1987: Aiming at the effect and economy of $CO_2$ enrichment. With combined calculation in the autumn sets (n=53) MGRs are underestimated, in winter sets (n=59) they are overestimated (interpretation see Krug 2002, p. 123). For a combined calculation the season term (st= $f_0$+$f_1$∗z) has to be added. More parameters see Mann 1986 table 9 and 11.
[b)]Rippen 1993; Rippen and Krug 1994; Rippen et al. 1994: Experiments in 27 holdings at 5 sites in Germany, 31 sets, no significant seasonal effect. Cvs. 'Ravel', 'Vivaldi', 'Talent', 'Arcade', 'Juliet', 'Deci minor', 'Bellura'.
[c)]Alscher 1993; Alscher et al. 2001a, b, c (4 phases model): Aiming at on-line control of temperature and $CO_2$ by combining a regression model with the Sucros-model. [1)]To be continued by a coeff. for planting weight (g): −0,286174. Growth simulation for phases 1–3 by equation 7, in phase 4. Alscher (1993) used the approximation GR = exp(log(100)+RGR)−100.

Kohlrabi (*Brassica oleracea* L. var. *gongylodes*) (Table 6 and Table 7).

Table 6. Kohlrabi (*Brassica oleracea* L. var. *gongylodes*): Transplant phase

| Reference | Cultivar/ weight ($g\ FW_{tuber}$) | Season sowing/ planting | Parameter/ ( ) = function | A | $c_1$(Ta) | $c_2$($S_i$) | $c_3$(C) | Min values | Ranges Ta Si C |
|---|---|---|---|---|---|---|---|---|---|
| [a)]K. & L. 1988 | 'Prima Vera' 3 g | Oct.–May | MGR ($g\ d^{-1}$) MR (4) | | | | | 0 70 – | 5–14 280–2800 350 |
| [b)]B. 1990 | 'Trero' 4 g | Oct.–Feb. (pricking) no st | MGR ($g\ d^{-1}$) MR (4) | 0,259 | −0,06435 | −0,17767 [1)] | −0,009316 | 0 16 100 | 16–18 200–2400 380 |

[a)]Krug and Liebig 1988: Calculation of the growth function; no significant season effect; parameters not retained, diagrams only, scaling of emergence dates for equidistant planting dates; effects of low temperatures (blindness, bolting).
[b)]Brückner 1990: Aiming at incorporation of artificial light into the response surface. [1)]$c_2(S_i) * (1{,}397679S_k + Si)$. The factor for Sk, derived by iteration, deviates from 1,8 in other calculations (Brückner 1990, table 10).

Table 7. Kohlrabi (*Brassica oleracea* L. var. *gongylodes*): Planting to harvest phase

| Reference | Cultivar/ weight (g FW) | Season sowing/ planting | Parameter/ ( ) = function | A | $c_1$(Ta) | $c_2$($S_i$) | $c_3$(C) | Min values | Ranges Ta Si C |
|---|---|---|---|---|---|---|---|---|---|
| [a)]M. 1986 | 'Trero' 60 g | Sep.–Oct. | MGR | 2,411 | −0,10250 | −0,00228 | −0,00825 | 2 | 3–18 |
| | | Jan.–Mar. | ($g\ d^{-1}$) | 2,438 | −0,09184 | −0,00174 | −0,00985 | 70 | 170–2400 |
| | | | MR (4) + st | 3,318 | −0,04704 | −0,00320 | −0,00932 | 100 | 300–1200 |
| | | Sep.–Mar. | | 3,546 | −0,58710 | −0,00132 | −0,00874 | | |
| [b)]B. 1990 | 'Trero' 50 g | Nov.–Feb. | MGR | 2,315 | −0,13505 | −0,10006 [1)] | | 0 | 10–18 |
| | | | ($g\ d^{-1}$) | | | | | 21 | 280–1800 |
| | | | MR (4) | | | | | 100 | 380 |

[a)]Mann 1986: In general the same results as with lettuce. More parameters see Mann 1986 table 9 and 11.
[b)]Brückner 1990: Aiming at incorporation of artificial light into the response surface. [1)]$c_2(S_i) * (1{,}363360\ S_k + S)$

Lamb's lettuce (*Valerianella locusta* L.) (Table 8).

Table 8. Lamb's lettuce (*Valerianella locusta* L.). Transplant phase

| Reference | Cultivar/ weight (FW g) | Season sowing/ planting | Parameter/ ( ) = function | A | $c_1$(Ta) | $c_2$($S_i$) | $c_3$(C) | Min values | Ranges Ta Si C |
|---|---|---|---|---|---|---|---|---|---|
| [a)]M. 1986 | 'Vit' 2 g | Sep.–Oct | MGR | 57,41 | −0,2186 | −0,00272 | −0,00851 | 2 | 3–18 |
| | | Jan.–Mar. | ($g\ d^{-1}$) | 59,36 | −0,2457 | −0,00174 | −0,00926 | 70 | 170–2400 |
| | | | MR (4) + st | 52,29 | −0,2134 | −0,00305 | −0,00928 | 100 | 300–1200 |
| | | Sep.–Mar. | | 65,27 | −0,1990 | −0,00133 | −0,00848 | | |

[a)]Mann 1986: Aiming at the effect and economy of $CO_2$ enrichment. In general the same results as with lettuce. More parameters see Mann 1986 table 9 and 11.

Cucumber (*Cucumis sativus* L.) (Table 9).

Table 9. Cucumber (*Cucumis sativus* L.)

| Reference | Cultivar/ weight (FW) | Season sowing | Parameter/ ( ) = function | A | $c_1$(Ta) | $c_2$($S_i$) | $c_3$(C) | Min values | Ranges Ta Si C |
|---|---|---|---|---|---|---|---|---|---|
| [a)]R. 1993; | 7 cvs | spring | duration | 156,3 | −0,0475 | −0,00019 | | 0 | 15–24 |
| R. & K. | planting→1 | plantings | t (6) | | | | | 0 | 1000–2000 |
| 1994; | kg fruits | 54 | | | | | | 0 | uc |
| R. et al. | 1 kg fruits→ | 49 | [1)] | | | | | | 14–22 |
| 1994 | final harvest | | | | | | | | 1000–2600 |
| | | | | | | | | | uc |

[a)]Rippen 1993; Rippen and Krug 1994; Rippen et al. 1994: Based on Liebig 1985. Data collection at 5 sites with 27 holdings in Germany, transplants grown in 21 °C, not grafted, planting interpolated to 600 $cm^2$ leaf area; duration overestimated at temperatures <18 °C.
[1)]Fruit weight was calculated in two steps: 1) an equation to describe the dominating seasonal trend of fruit yield ($FB_{(W)}$) and 2) an equation to consider the actual growing conditions:

1) $FB_{(w)}=2{,}3944+0{,}042397*\sin(2\Pi*cw*52^{-1})-0{,}96900478*\cos(2\Pi*cw*52^{-1})$ (13)

2) $FR_{(w)}=FB_{(w)}+8{,}0456493-1{,}035767*Ta+0{,}0025538748*Si-2{,}5178467*cw^{-1}+0{,}026395095*Ta^2+0{,}00000024798383*Si^2-0{,}00014110296*Ta*Si+0{,}34640049*Ta*cw^{-1}-0{,}001002008*Si*cw^{-1}$ ($R^2$= 0,35) (14)

Asparagus (*Asparagus officinalis* L.) (Table 10).

Table 10. Asparagus (*Asparagus officinalis* L.)

| The effect of temperature, light and soil resistance on length growth rate and fresh weight of spears is given by: | | |
|---|---|---|
| $Temperature_{(0–20\ °C)}$: | MGR (cm $d^{-1}$) =−4,9+0,44 T+0,29 $H_{(0–20\ cm)}$ | (15) |
| $Light_{(0–18\ klx)}$: | MGR (cm $d^{-1}$) = 1,44+0,01 L +0,2 $H_{(0–20\ cm)}$ (not signif.) | (16) |
| Soil resistance: | MGR (cm $d^{-1}$) = −1,12−12,1 SR | (17) |
| Fresh weight: | MGR (g $d^{-1}$) = −0,07+21,8 FW | (18) |
| Pooled: | MGR (g $d^{-1}$) = c+a * T+b * H+e * SR | (19) |

*Definitions and abbreviations*

a = constant or adjustment parameters for basic yield; A= theoretical maximal value of plant weight; b = adjustment parameters for $FR_{(w)}$; b, c, f, k = coefficients; C = $CO_2$-concentration (µl $l^{-1}$); Cmin = compensation point (µl $l^{-1}$); cw = calendar week; DW = dry weight; em = emergence; $FB_{(w)}$= basic yield per week; $FR_{(w)}$ = yield in fruits $m^{-2}$ $week^{-1}$; FW = fresh weight; GR = growth rate (MGR, AGR or RGR)]; LTN = long term normals; MGR = Mean growth rate; MR = Multiplicative regression function; MLR = Multiple linear regression; PM = half time of the phase; RGR = Relative growth rate; S= irradiance of global radiation or PAR (Wh $m^{-2}$ $d^{-1}$), mean daily sum of irradiance (Wh $m^{-2}$ $d^{-1}$); Si = global irradiance inside (Wh $m^{-2}$ $d^{-1}$); st = season term; Sk = artificial irradiance (Wh $m^{-2}$ $d^{-1}$); Smin = compensation point of irradiance (Wh $m^{-2}$ $d^{-1}$); SR = soil resistance (0–1,5 kg $cm^{-2}$); T = mean temperature (°C); t = time (primarily days), duration of the phase in days; Ta = temperature air (°C); Tmin = basic temperature (x for y=0, GR=0), theoretical temperature minimum (°C); Ts = soil temperature (°C); $Ts_{min}$ = basic soil temperature (°C); uc = uncontrolled; z = half time value of the cultivation period (Weber and Liebig 1981); Z = days since October 1st;

## Concluding remarks

This compilation of more than three decades research, primarily in vegetable greenhouse production, based on a just arising discipline with a rapidly developing computer technology, suffers from antiquated hard- and software, lost or not more readable programs or data and also by incomplete particulars in publications. These deficiencies and diversities complicate a survey, which shall be reduced by this summarising review. Beyond this contribution some missing data may be derived from the diagrams published on the response surfaces and by studying the original and especially the summarising publications (Krug and Liebig 1984b; Krug 1997; Krug et al. 2007a, b). The data, functions and respective software are available from Krug et al. 2008.

Till now the results attained are far from covering the totality of vegetable production systems, as wanted to optimise rotations with all their new technical achievements, new cultivars with all the associated ecological and economic aspects. But for commercial practise and advice they offer much assistance for decisions in production subsystems: To arrange small, short-lived crops into rotations, to estimate opportune input-factor intensities, the gross marginal or the 'return minus factor cost', they also allow for timing a crop or on-line control of growth and/or development on a daily base. Moreover, case studies in terms of optimising by iteration are enabled. But for completion data acquisition and approaches have to be extended and updated.

For open field production only a few experiments have been carried out with radish (*Raphanus sativus* L. var. *sativus*, Krug and Fink 1991). The levels of the morphological components of growth (Leaf Weight Ratio, Specific Leaf Area, Leaf Area Ratio) were about identical, when grown in the open field, greenhouses and growth chambers. Net Assimilation Rate was somewhat lower in greenhouses and distinctly lower in the field, compared to values in growth chambers. The authors discuss possible explanations. The qualitative reaction patterns of growth components to temperature and irradiance, however, were about equal and offer a good chance to model outdoors growth.

Beyond these practical aspects these models allow case studies in research to prepare experimentation and to reduce mechanistic (sub)models to computable software, termed summary models (Matitschka 1995). For research and teaching the understanding of the innumerable relations and interrelations in production systems has grown and may help in decision-making and can be a useful tool in advice. Modelling should facilitate and encourage exact, i.e. mathematical thinking in understanding, planning and control. It cannot and shall not replace the practical experiences, but shall help to base it on a well-grounded basis.

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