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Modelling Production Subsystems at High Abstraction Level – Reviewing Summary. I. Basic Considerations and Approaches

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Summary

In 35 years modelling in vegetable production in the Institute of Vegetable Crops (now Institute of Biological Production Systems, Section Vegetable Systems Modelling), Leibniz Universität Hannover, resulted in numerous theses and articles, using different approaches, computer techniques and software, complicating a survey. Part I of this contribution tempts to review and summarise the approaches and experiences with respect to the basic conditions to facilitate further research.

Key words. climate data acquisition – growth function – growth efficiency – response surface – planning model – control model

Introduction

Modelling plant growth was initiated by De Wit and Brower [(1968), for a review see Krug 2004]. Subsequently, several researchers started modelling growth and development of crops associated with greenhouse climate, using different approaches and options. The team in the Institute of Vegetable Crops, University Hannover, started modelling to answer questions in vegetable production upraised by the energy crisis in 1973. This had demanded to include economic aspects and – as far as possible – to consider total rotations. This means that growth models of as many crops as possible should be elaborated. Considering the extent and complexity of this challenge, simple approaches at high abstraction level were preferred (and should always be preferred in complex systems by system theoretical reasons, Vester 1984). In the initial phase computer languages nowadays considered outdated had to be used and different operations were tested, complicating the assembling. Therefore, the author aims to summarise and to update the plurality of investigations by composing main equations, parameters and reconsidering problems involved to facilitate handling, application and further research. In part I the basics are considered. The acquired parameters of vegetable species will be presented in part II.

Approaches

Definitions and Abbreviations. a = constant or adjustment parameters for basic yield; A = theoretical maximal value of plant weight; AGR = Absolute Growth Rate; b, c, f, k = coefficients; C = CO_2-concentration (µl l^{-1}); Cmin = compensation point; FW = fresh weight; GR = growth rate (MGR, AGR or RGR); MGR = Mean Growth Rate; PM = middle of the phase; RGR = Relative Growth Rate; S = irradiance of global radiation or PAR (Wh m^{-2} d^{-1}), mean sum of irradiance per week (Wh m^{-2} d^{-1}); Si = global irradiance inside (Wh m^{-2} d^{-1}); Sk= artificial irradiance; Smin = compensation point of irradiance; st =season factor; T = mean temperature (°C); t = time (primarily days), duration of the phase (in days); Ta = temperature air (°C); t_f = time of final weight; t_i = initial time; Tmin or Ta_{min} = basis temperature (x for y=0, ER=0), theoretical temperature minimum; Ts = soil temperature (°C); Ts_{min} = basic soil temperature; W = weight; W_f = final weight; Wi or Wo= initial weight.

Data acquisition was focused on climatic factors in greenhouses (natural and artificial radiation, air and partly soil temperature, CO_2-concentration). Other factors affecting growth (inter alia nutrients, water) were kept constant as far as the equipments admitted. Temperature was varied by heating and ventilation, irradiance by planting in different seasons and intensified by artificial light, CO_2-concentration by enriching with CO_2-gas and soil temperature by soil heating with pipes. The intensities of the climatic factors in the experiments were measured as described by Krug and Liebig (1979).

To estimate the *climatic conditions* of particular sites the data were compiled from meteorological tables. To consider seasonal trends daily means of **Long Term Normals** (LTN, means of about 30 years) were used. Since these data suppress the diurnal and annual fluctuations, the implications on crop growth were compared to those of most favourable and moist unfavourable ones out of 36 years (1956–1992, Krug and Liebig 1988). The simulations, starting at the beginning of the respective periods, resulted in medium to small variability in winter and spring plantings, but large annual deviations in autumn plantings. Starting with the ends of the periods, annual deviations were large in spring and small in autumn and

winter sets. The causes are discussed by KRUG (2002). The LTN derived were processed for the particular conditions, first by regression models derived from the experiments (KRUG and LIEBIG 1979), later on by the more sophisticated model of Rath (unpublished, in prep.), considering different greenhouse constructions and equipments on a hourly basis (see KRUG et al. 2007a, b).

To consider annual significant recurring deviations from the smoothed course of LTN, KRUG et al. (2007 a, b) tested the suitability of **Reference Years** (BLÜMEL et al. 1986). These proved adequate to forecast the most probable climate for special periods, to derive seasonal trends of crop growth, however, LTN were preferred.

For data collecting crops were grown with production techniques corresponding to commercial practice. Growth was measured repeatedly by destructive methods, if possible by non-destructively ones: Dry weight increase, in case of approximately constant water status of the plants also by fresh weight increase as well as dimensions of volume. These data were parameterised by **growth functions.** Adjustments depend on the course of the growth curves: Young plants generally grow exponentially, turning into a more or less linear growth phase, older plants thereafter turn into a declining growth phase. The turnover points depend on species and environmental conditions, especially on the season. In autumn, for example, the turnover from the exponential phase to the linear or already declining one occurs earlier, due to the deterioration of growing conditions; on the other hand the exponential phase lasts longer in spring, due to improving growing conditions. Adaptable growth functions are compiled by BAZLEN [(1985), see also KRUG 1997, p.133]. The following growth functions proved most suitable:

Exponential growth: $$W(t) = W_0 * \exp(RGR * t) \quad (1)$$

Logistic growth (S-shaped): $$W(t) = W_0 + A * [1 - \exp(b + k * \ln(t))]^{-1} \quad (2)$$

The growth functions allow calculating **growth efficiency** more precisely than the data measured in intervals. Growth efficiency can be described by periods (mostly days) to reach a defined stage of growth or development, a stage of production techniques (e.g. sowing, emergence, planting, criteria of harvesting) or by derived criteria, such as the Mean Growth Rate [MGR = $(W_2 - W_1) * (t_2 - t_1)^{-1}$, index 2 = means the end and index 1 the start of the respective period], as a linear approach to the respective period; the Absolute Growth Rate (AGR = $dW * dt^{-1}$) as the gradient at a defined point of time and the Relative Growth Rate (RGR = $(dW * dt^{-1}) * W^{-1}$) as the absolute increase at a defined point of time related to the respectively preceding value or accordingly the Mean Relative Growth Rate.

To relate growth efficiency to the growth factor intensities **response surfaces** were calculated (growth parameters as a function of growth factor intensities). Problems may arise by changing plant reactions during ontogenetic growth/development. A drastic example is the emergence phase compared with autotrophic growth. Young plants react stronger to temperature than to irradiance; older ones react stronger to irradiance than to temperature when the leaf area approaches the optimal Leaf Area Index (KRUG 1997, 2002). Therefore, the response surfaces change with growth/development.

In general, for each day a special response surface can be calculated. For periods with constant growth efficiency criteria, however, as for example RGR during exponential growth, AGR or MGR during linear growth, plant response can be represented by a uniform response surface. This period is defined as a **growth phase**. Phases can also be generated by a change–over in the development of a plant (e.g. vegetative to generative) or by technical interferences, such as planting or harvesting. To calculate long-term on-line growth, the total period has to be divided into respective growth phases, each with its own response surface.

The calculation of response surfaces for the heterotrophic emergence phase is described in part II. For the autotrophic period, at the beginning the Multiple Linear Regression function was adopted to specify climate reactions (KRUG and LIEBIG 1979, GR for MGR, AGR or RGR):

$$GR = a + c_1T + c_2S + c_3T^2 + c_4S^2 + c_5T * S \quad (3)$$

This equation, however, resulted in unrealistic growth values in the border areas (e.g. at low temperatures), especially when extrapolated, and in crossovers when interactions were involved (MANN 1986, 1987). Therefore a Multiplicative Regression Function, deduced from MITSCHERLICH [(1919); KRUG and LIEBIG 1984] was preferred. Preconditions are that the acting factors should not be correlated with each other in order to avoid confounded correlations; the ranges of the intensities of the growth factors remain in the saturation region (exception see equ. 5); the intensities of the growth factors do not fluctuate far beyond the buffer capacity of the crops in the respective phase and the special basic conditions do not change severely (e.g., exhaustion of a non considered growth factor (e.g. water, nutrient elements, damage by pests or diseases and others). The Multiplicative Regression Function reads (GR):

$$GR = A * [1 - \exp(c_1 (Ta - Ta_{min}))] * [(1 - \exp(c_2 (1{,}8 * Sk + S - S_{min}))] * [1 - \exp(c_3 (C - C_{min}))] * [1 - \exp(c_4 (Ts - Ts_{min}))] \quad (4)$$

The factor 1,8 for Sk compensates the high fraction of PAR of artificial light, when natural light is declared as global irradiance with about 50 % PAR. This value depends on the artificial light source and the intensity of the natural light (particulars see BRÜCKNER 1990, pp. 44). If a declining phase is following, as for example when temperature optimum is overshot, an additional term has to be added (up to now, however, only little experience exists):

$$GR_n = GR * [1 - \exp(+c(x_{n+1} - x_{n+1min}))] \quad (5)$$

As an example the response surface of lettuce transplants to four climatic factors (soil temperature is omitted) is presented in Fig. 1.

The **parameter A** is defined as a physiological item, but with young growth/development phases the extrapolated values are far off the real maximum weight. Since early harvesting happens for many vegetable crops – contrary to most agriculture crops – follows a large variation in a statistically estimated A. Moreover, this value results from the main actions and in addition the interactions of the affecting growth factors, thus it is only constant for a special constellation of the environmental factors. Therefore, it cannot be generalised and has to be considered a working variable.

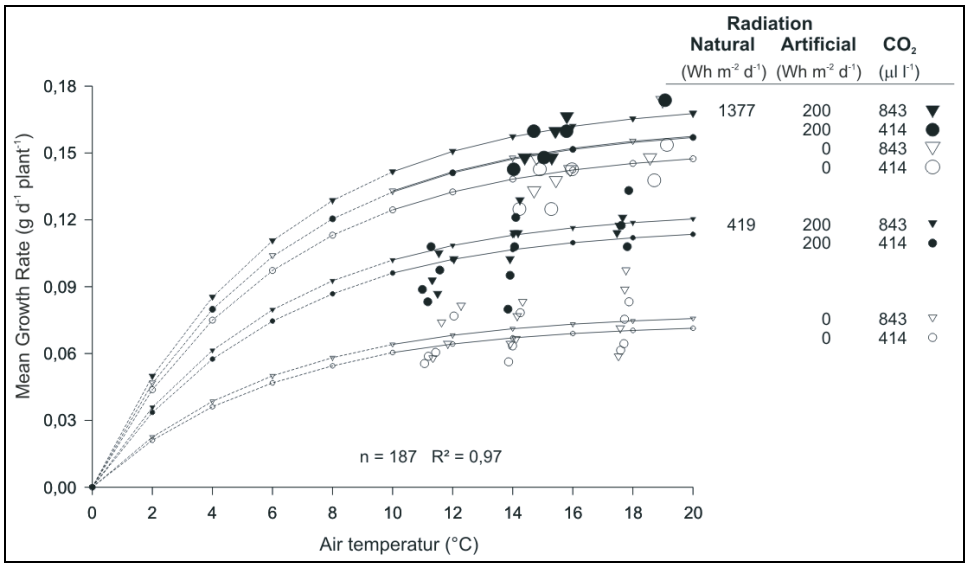


Fig. 1. Response surface of Mean Growth Rates of lettuce transplants (emergence to 4 g fresh weight), representing the effects of the intensities of four growth factors (soil temperature = 15 °C, T_{min} = 0 °C, KRUG and LIEBIG 1994).

The **min-parameters** mean the x values for y = 0 or physiologically the compensation point for irradiance or CO_2-concentration and the lower border temperature for growth and therewith they are physiologically interpretable. When an adequate number of measured low values are available, they can be determined statistically by iteration (see BRÜCKNER 1990). Otherwise they can be determined by special physiological experiments (see MANN 1986, 1987 for CO_2). In the latter case they stabilise the curves in the lower region. A realistic min-value is especially important, when a linear relation is calculated (e.g., temperature in the emergence phase (LEDERLE et al. 1984)). When values in higher regions are of dominant interest, for example with CO_2 concentrations >350 µl l^{-1}, some variability of the min-value had little influence using the Multiplicative Regression Function (MANN 1986, Fig. 10). Interactions in plant response to the growth factors will only marginally cause variation of the min-values. Greater effects may be expected by the duration of the exposure, e.g., to low temperature.

The **coefficients** were considered factor specific constants by MITSCHERLICH (1919) for his mono-causal relationships in the comparable environments in his agriculture production systems. In the response surfaces discussed here, however, the relationships are multi-causal and like parameter A they depend on the interacting effects of the input factors. Therefore, it was tested, whether the seasonal circulating intensities of the growth factors under consideration would cause significant effects on the coefficients. This was checked by dividing the October–May season into an autumn–winter and a winter–spring season or, alternatively, by introducing a season term (st) (WEBER and LIEBIG 1981; KRUG and LIEBIG 1988):

$$st = + (a + b * \sin x + c * \sin 2x + d * \cos x + f * \cos 2x \quad (6)$$

($x = 2\ \Pi\ PM * 365^{-1}$).

A seasonal effect could be significantly verified in some investigations, in others not (Table 1). These different results can be explained by weather effects, by different precision in the performance of the experiments and/or evaluation, by random effects, perhaps also by the species and the duration of the respective growth phase. In general, it can be concluded that a season effect does exist and has to be considered in seasonal encroaching calculations. It has to be examined whether mechanistic models can better describe seasonal effects.

On the basis of the greenhouse climate data and the response surfaces growth models were developed. If the duration of the phases is requested only, as for production planning, a linear approach, calculations with the MGR, proved adequate and is referred to as **planning models** (KRUG and LIEBIG 1984, 1994):

$$t_2 - t_1 = (W_2 - W_1) * MGR^{-1} \quad (7)$$

The calculation schema is presented in Fig. 2. To establish diagrams, the duration was estimated first for mean factor intensities of an expected period. Since these will deviate from the intensities of the finally calculated period, the procedure was repeated until the preset duration agrees with that calculated, which means by iteration.

In the first investigations the starting point was the inception of the growth phase. In production planning, however, the reverse question is also of interest: E.g., which date of planting has to be chosen for a predetermined time of harvesting. In this case iteration had to be started at the end point. Due to inaccuracies of the estimations, both lines differ more or less. To establish a diagram allowing readings in both directions, an approach was developed to start in the middle of the period (WEBER and LIEBIG 1981) and the results are demonstrated in a diagonal-diagram (Fig. 3). The duration is presented by the distances between the diagonal and the respective calculated curves. In the diagonal diagram additionally the differences between the curves atop the x-axis (time of the final points) as well as atop the y-axis (time of the starting points) can also be clearly demonstrated. Examples for application are to calculate mean favourable set points for factor inputs, e.g. heating (KRUG 2002, Figs. 5-3, 5-6, 5-7, 5-8, 6.1-21), to plan distances between sowings or plantings for continuous harvesting (KRUG 2002, Figs. 5-11, 5-12), or optimisation of rotations (KRUG 2002, Figs. 5-10).

If the on-line course of growth is of interest, as for on-line climate control, in the exponential range the RGR or

Table 1. Significance of a seasonal effect in respective investigations.

Crop		Season effect	
		significant	not significant
Radish (var. *sativus*)		Krug and Liebig 1979	Rippen 1993
Radish (var. *niger*)		Mann 1986, 1987	Krug and Liebig 1984
Lettuce:	transplants	Krug and Liebig 1988	Krug and Liebig 1994
	planting–harvest	Mann 1986	Rippen 1993
Kohlrabi:	transplants		Krug and Liebig 1988; Brückner 1990
	planting–harvest		Mann 1986; Brückner 1990
lamb's lettuce		Mann 1986	

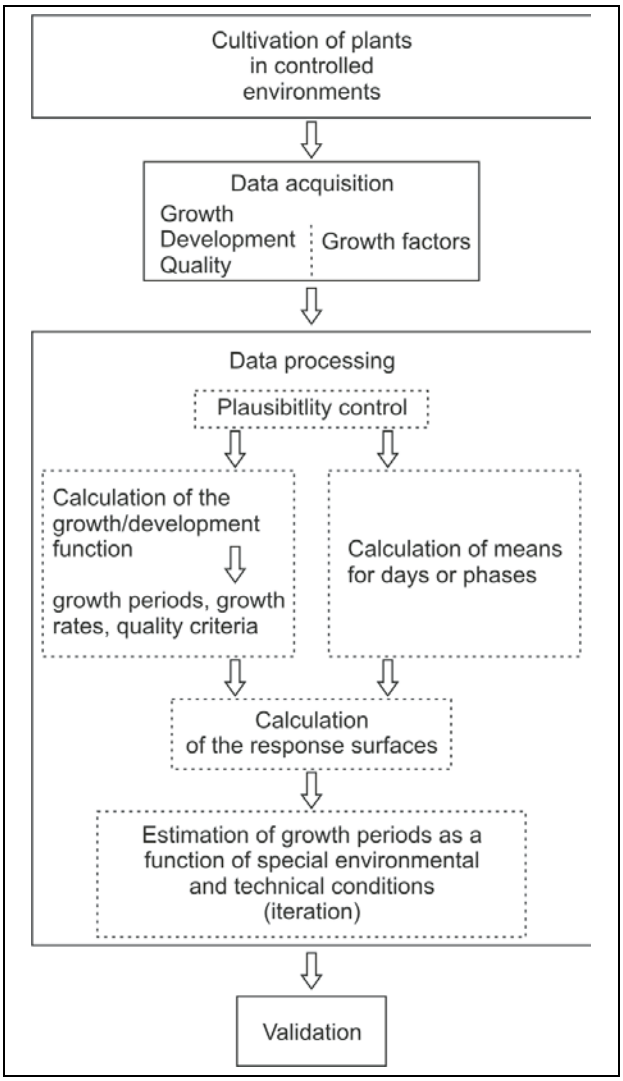


Fig. 2. Procedure of modelling long term plant growth (planning model) using regression models (Krug and Liebig 1994).

in the linear range the AGR are adequate. This approach is referred to as **control model** (Krug and Liebig 1984, 1995; Krug 2002, Figs. 5-13). When tested, both approaches, the planning and the control model, resulted in nearly identical periods. The shortest time interval of the control model, however, is a day (24 hours, Krug and Liebig 1984). Shorter periods have to be considered by more mechanistic approaches (details see Alscher 1993 and Alscher et al. 2001a, b, c). Another application is the prediction of dates of interest (e.g. planting time, harvest date).

In on-line control models growth was simulated by:

Exponential growth: $\ln W_f = \ln W_0 + RGR_1 + RGR_2 + \ldots + RGR_n$ (8)

or: $W_f = \exp(\ln W_0 + RGR_1 + RGR_2 + \ldots + RGR_n$ (9)

or: $W_{(d)} = W_0 * \exp(\Sigma RGR_{(i)})$ (10)

Linear growth: $W_f = W_0 + AGR_1 + AGR_2 + \ldots + AGR_n$ (11)

or: $W_{(d)} = W_0 + \Sigma AGR_{(i)}$ (12)

An example is presented in Fig. 4. In case of radish (var. *sativus*), which is grown in its vegetative phase, the division into 4 growth phases proved best and the approach on the basis of weight proved as good as the approach on the basis of physiological parameters [Net Assimilation Rate, Leaf Area Ratio, Leaf Weight Ratio, Specific Leaf Area (Bazlen 1985)]. In case of more developmental processes, e.g. flower differentiation, modelling on a physiological basis should be preferred.

A comprehensive **economic valuation** demands complete rotations. This requires Linear Programming, as demonstrated in Krug 2002 (Figs. 5-10) and will be difficult to model, when all the crops and cultivars as well as environmental and technical dependencies have to be considered. A valuable decision support, however, is already the calculation of the gross marginal or the return minus factor cost (e.g. heating, examples see Krug et al. 2007a, b) of single crops.

To calculate energy demand for heating greenhouses the models of Vickermann (1969) and Damrath (1980) were initially used. Based on daily means (Vickermann 1969) and not considering heat storage in the soil in both models, they misjudge the required energy quantities. Therefore, hourly and daily means and sums were generated by the climate model of Rath (unpublished, in prep.) and the energy demand for heating (according to Rath 1994) is calculated on hourly basis for the respective conditions considering ventilation, heat storage in the soil and wind speed. The older results, calculated for small greenhouses, however, coincide well with the values of Vickermann (1969), calculated for large greenhouses as used in commercial practice, and so the earlier derived economic recommendations turned out to be still valid.

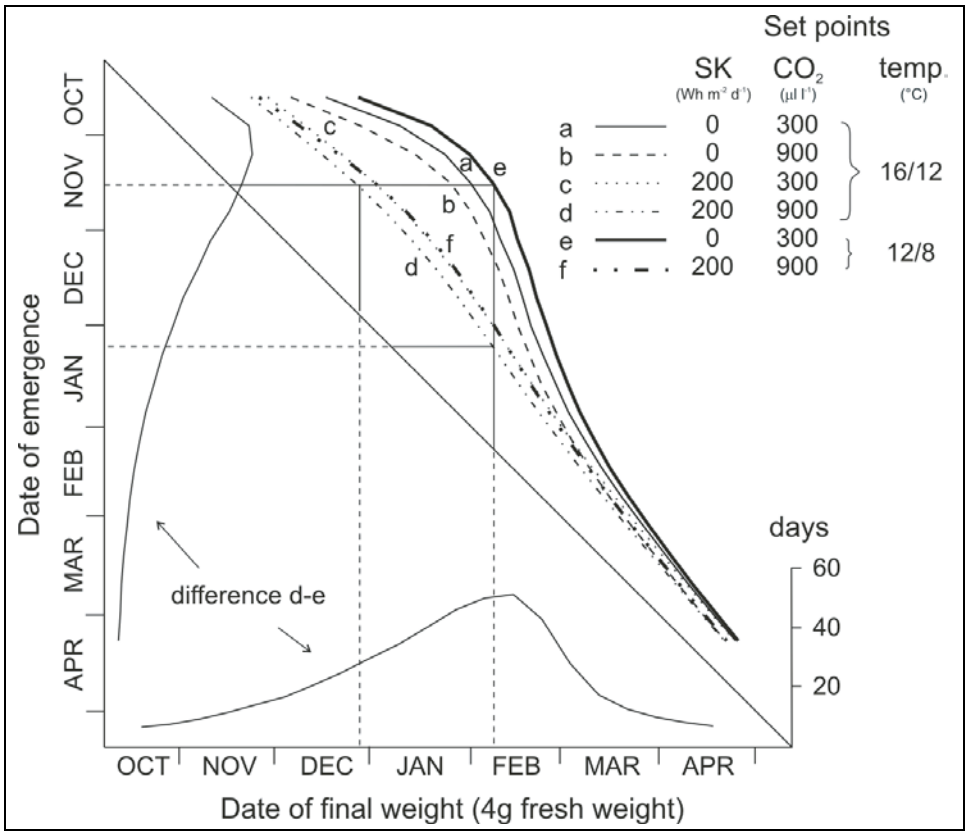


Fig. 3. Raising periods of lettuce transplants (emergence – 4 g fresh weight) as a function of factor intensities in a diagonal presentation, allowing for bilateral readings. Atop the coordinates differences, transferred from the diagonal graph (Sk = artificial light, dimensions see Fig. 1, KRUG and LIEBIG 1994).

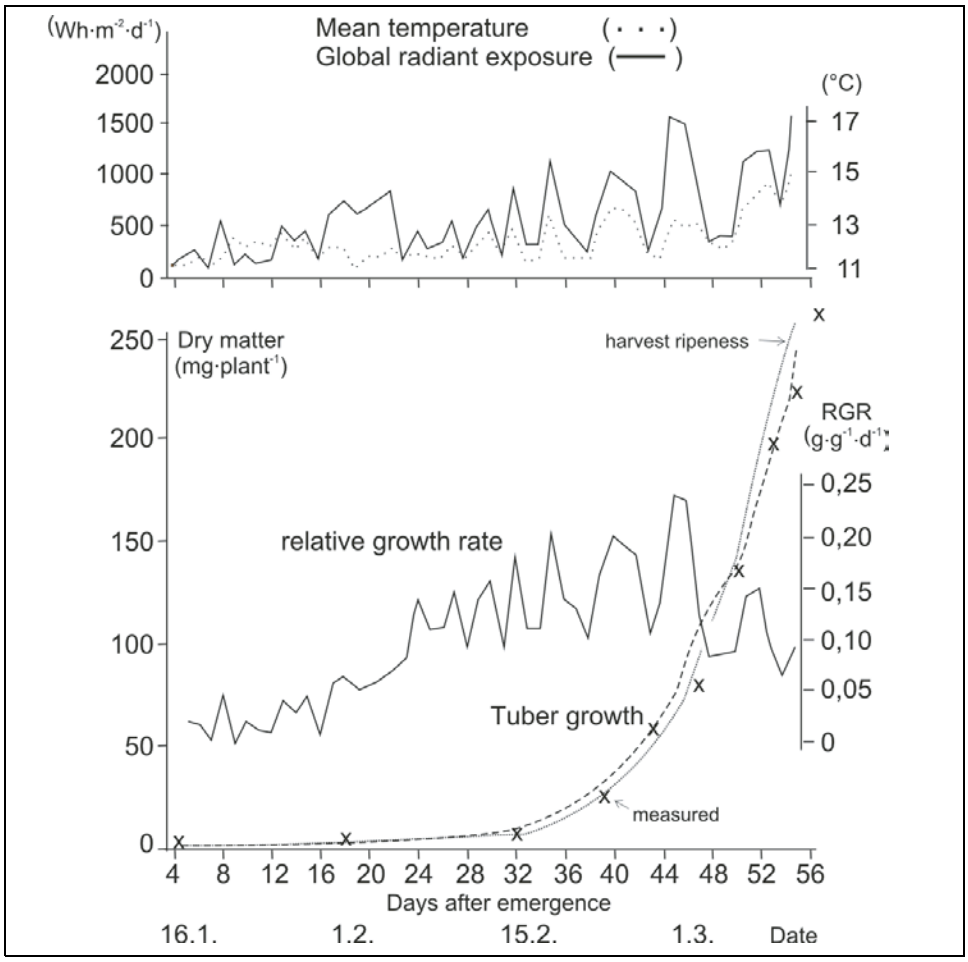


Fig. 4. Simulation of growth of radish tubers (var. *sativus*) based on RGR for formal phases (weight, –––) and physiological phases (.....) as a function of irradiance, temperature and ontogenetic stage (details see BAZLEN 1985).

The calculated parameters and concluding remarks will be presented in part II.

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